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Planning Report

Metrology-Related Costs in the U.S. Semiconductor Industry, 1990, 1996, and 2001

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Metrology-Related Costs in the U.S. Semiconductor Industry, 1990, 1996 and 2001

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I. Introduction

This study estimates the amount of metrology-related costs in the semiconductor industry, including the industry's infrastructure, for 1990 and 1996 along with a projected range for 2001. It is the first study that determines the size of metrology-related costs across all metrology-intensive segments of the semiconductor industry, including the industry's infrastructure. "Metrology-related costs" in this study is the value of current period spending by the semiconductor industry to acquire what we designate as "metrology capability." Because we limit metrology-related costs to current spending for equipment, we use the terms "metrology costs" and "metrology investment" interchangeably.

This study was prepared under the sponsorship of the National Institute of Standards and Technology ("NIST") in order to provide NIST with a better understanding of metrology investments made by the U.S. semiconductor industry. NIST's interest in this issue arises out of its mission to work with U.S. industry to develop and apply technology, measurements, and standards.

> NIST's mission is straightforward and unique…NIST promotes U.S. economic growth by working with industry to develop and apply technology, measurements and standards -- providing the basic technical infrastructure needed by U.S. industry. We concentrate on industry because it is industry that transforms

> technology into the products and services, the profits and jobs that yield the true returns to American taxpayers.[1]

In the case of the semiconductor industry, it is NIST's Office of Microelectronics Programs ("OMP") that has the responsibility to integrate NIST's research program with the needs of the U.S. semiconductor industry.[2]

This study is not an assessment of metrology technology characteristics nor does it identify new metrology applications in the semiconductor industry. Metrology technology requirements are spelled out in the Semiconductor Industry Association ("SIA") technology roadmap, *The National Technology Roadmap for Semiconductors – Technology Needs*, 1997.[3] The SIA Roadmap defines metrology technology requirements related to microscopy, sensors, materials and contamination, and reference materials.[4] Our definition of metrology differs from the one applied in the SIA Roadmap because it expressly excludes costs associated with *in situ* metrology capabilities. According to the SIA Roadmap, "[m]etrology must migrate from off-line to in-line and *in situ* to achieve the Roadmap goals. While installing *in situ* capabilities

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[1] Statement of Arati Prabhakar, Director, National Institute of Standards and Technology Before the Subcommittee on Commerce, Justice, State, The Judiciary, and Related Agencies, Committee on Appropriations, House of Representatives, March 15, 1995.

[2] OMP works with the Semiconductor Industry Association ("SIA"), the Semiconductor Research Corporation ("SRC"), SEMATECH, and other organizations.

[3] Hereafter, "SIA Roadmap."

[4] SIA Roadmap, p. 179.

may emerge as a major cost for the semiconductor industry in the future, we do not speculate about its potential impact.[5]

Organization of Report

We made a significant effort to develop definitions for metrology activities and costs as they relate to the semiconductor industry. Some background may be helpful to explain why this was necessary. Section II discusses in detail the definitions we apply in this study. Understanding these definitions is important to correctly interpreting our results.

In originally designing the research strategy for this study, we believed that we could rely on a mail survey instrument to collect market data together with follow-up interviews. However, once we commenced the study it soon became apparent that this approach was not workable. During meetings with experts knowledgeable about metrology applications in the semiconductor industry at NIST, and later at SEMI/SEMATECH and SEMATECH, we learned there was not widespread agreement on what constituted metrology activities in the semiconductor industry. Furthermore, no single person was capable of defining the scope of the entire metrology-related "industry." Our first task, therefore, became to develop a set of definitions to apply in structuring the data collection effort, including a taxonomy of metrology activities in the

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[5] See S. Butler, J. Hosch, A. Diebold, and Brad Van Eck, "Sensor Based Process and Tool Control," *Future Fab International*. According to them, the 1994 Roadmap suggested that a shift from off-line and in-line metrology to sensor-based process and tool control was coming, most likely in connection with the implementation of process tools for 300mm wafers.

semiconductor industry. This was accomplished through extensive interaction with NIST, SEMI/SEMATECH, and SEMATECH. At the same time, we identified other experts who could provide information on specific metrology activities in the semiconductor industry.[6] These experts provided details on metrology functions and also identified some of the leading firms supplying metrology capabilities to the semiconductor industry.[7,8]

Section III provides our estimates of U.S. metrology-related costs for the U.S. semiconductor industry for 1990 and 1996. We developed our estimates using two methods: (1) a “supply side” approach that relies upon identifying all metrology firms and totaling their metrology-related revenues, and (2) a “demand side” approach that relies on determining metrology-related costs for four segments of the semiconductor industry that utilize metrology the most intensively. We also benchmark our estimates for growth of metrology-costs between 1990 and 1996 by making comparisons to the growth of total semiconductor device and semiconductor equipment revenues. This section also provides insights into the factors driving increases in metrology costs in the semiconductor industry. We extrapolate the trend in the growth of metrology costs to 2001 consistent with projections of the growth in the semiconductor industry.

[6] We also did a search of recent technical journal articles to identify experts in various technical specialties.

[7] Appendix C lists the individuals interviewed.

[8] We developed a questionnaire tailored to each metrology segment included in this report. Appendix D provides an example of the questionnaire used to collect data on the metrology equipment which measures electrostatic discharge in semiconductor clean rooms.

Five appendices provide supporting information. Appendix A defines "Measurement-Related Attributes." Appendix B lists the segments of the semiconductor infrastructure from which firms were identified as metrology suppliers to the semiconductor industry. Appendix C provides the list of individuals interviewed for this study. Appendix D provides an illustration of the survey form that was used to structure interviews. Appendix E lists the companies identified in the report as providing metrology capability to the semiconductor industry.

Acknowledgements

There are certain individuals who require special recognition because, as difficult as it was to develop a workable methodology to carry out this study, it would not have been possible absent the significant input of time from them: Robert Scace, NIST; Robert Bachrach, Applied Materials; Pat Gabella, SEMI/SEMATECH; and David Jensen, SEMATECH. I especially want to thank Alain Diebold, SEMATECH, who never failed to answer my questions with, what can only be described as, an encyclopedic knowledge of metrology-related topics.

II. Defining Metrology-Related Costs in the Semiconductor Industry[9]

This section presents the definitions used to structure the data collection process. Since it is the first study that measures metrology costs in all segments of the semiconductor industry "food chain" – semiconductor device manufacturers plus the infrastructure – some definitions differ from the most common usage in the semiconductor industry. Several definitions are even unique to this study. Because of these differences, it becomes particularly important to review all of the definitions presented here before interpreting the results provided in Section III. Why was it necessary to develop a special set of definitions? Certainly an industry studied as intensively as the semiconductor industry has already been thoroughly characterized. The answer is found in the breadth of the scope of the study: No previous study of metrology costs in the industry has attempted to measure metrology costs in all segments of the semiconductor industry food chain for all types of metrology activities.[10] Measuring the semiconductor industry's total investment in metrology capability required broader definitions of metrology investment than was used in prior evaluations. In addition, in order to identify a reasonable boundary for the scope of the study, it also required using a different definition for the semiconductor industry than the one that

[9] Again, as noted above, we are using the term "costs" interchangeably with the term "investments" for the purposes of this study.

[10] Market research firms such as VLSI Research and DATAQUEST, for example, routinely provide information on the size of the metrology equipment market. But, as explained in Section III, their data covers only a relatively small fraction of the total metrology supplying industry, as we define it.

was commonly applied. This alternative definition included certain segments of the infrastructure not normally considered to be a part of the industry because they are metrology intensive while simultaneously excluding certain segments, for reasons explained below, that are usually defined to be a part of the industry's food chain.

This section starts by specifying how we define metrology and the scope of the semiconductor industry for the purposes of this study. Our definition of the semiconductor industry spans both device makers and the industry infrastructure. This broad definition for the industry, in and of itself, is not new since it is based on the widely accepted concept of the industry's food, but it differs by limiting the industry's scope to four metrology-intensive segments. We then turn to the central issue: How to measure the semiconductor industry's investment in metrology capability for these four metrology-intensive segments?

A. Physical Measurements Important to the Semiconductor Industry

Broadly speaking there are two types of measurements performed in the semiconductor industry: physical measurement and final electrical test. We exclude final electrical test from the scope of this study because, traditionally, NIST is more focused on supporting physical measurements.[11] Our objective is to determine the semiconductor industry's investment in the infrastructure needed to support all types of physical measurements.

[11] It is not strictly correct that all forms of electrical tests are excluded. The experts we consulted recommended inclusion of in-line electrical test for resistivity as a physical measurement.

Physical Measurements

In the context of the semiconductor industry, physical measurement frequently refers only to physical measurements made as part of in-line process control. For example,

> The semiconductor industry refers to measurements used in process control as *metrology*. Engineers often use the word to describe procedures, such as critical dimension (CD) measurements, which routinely monitor lithography processes inside the clean room. Others generalize it to all in-line measurements. According to the dictionary, *metrology is the science of measurement*. It should also be noted that metrology includes all aspects both theoretical and practical with reference to measurements, whatever their uncertainty, and in whatever fields of science or technology they occur. The term characterization is also used interchangeably with metrology.[12]

This definition is too restrictive to be applied in this study because it fails to include off-line physical measurements and also implicitly limits measurement to "inside the clean room" (the wafer fabrication stage of semiconductor manufacturing).

We include all off-line measurements performed in all segments of the semiconductor industry when determining total spending on metrology equipment.

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[12] T. Shaffner, A. C. Diebold, R. C. McDonald, D. G. Seiler, and W. M. Bullis, "Business and Manufacturing Motivations for the Development of Analytical Technology for Semiconductors," in W. M. Bullis, et. al. ed*., Semiconductor Characterization, Present Status and Future Needs.* New York: American Institute of Physics: 1996, pages 1- 2.

Types of Physical Measurements Used in the Semiconductor Industry

Based on interviews, we identified 16 types of physical measurements used in the semiconductor industry.[13] These 16 measurements are listed in Table 1. (Appendix A provides more detailed descriptions.) The number of semiconductor equipment families that use each type of measurement is shown in the second column of the table. Time interval measurement is used almost in all types of semiconductor equipment while stress & strain and resistivity measurements are required in only one type of equipment.[14] In developing data on metrology costs, we determine the spending on hardware to support these 16 types of measurements.

B. Metrology-Intensive Segments of the Semiconductor Industry

Because the objective of this study is to extend NIST's knowledge about metrology activities in all segments of the semiconductor industry, we apply a broad definition of the "semiconductor industry." Specifically, this study includes significant portions of the industry's infrastructure in order to measure metrology activities at all levels of the industry's food chain, especially the more metrology-intensive segments.

[13] We prepared a list of measurement activities and then asked NIST, SEMI/SEMATECH, and SEMATECH representatives to comment on it. Table 1 presents the final consensus on the physical measurements required by the semiconductor industry.

[14] See Appendix A, Table A.1.

Table 1
List of Physical Measurements Used by the Semiconductor Industry

Measurement Category	Number of Semiconductor Equipment Tools Requiring This Measurement (out of 16 total tool families)
1. temperature gradient & absolute	13
2. physical dimensions thickness / weight / position	12
3. pressure total / partial	11
4. "dose" radiometry flux	7
5. optical properties intensity polarization spectral distribution / bandwidth	6
6. flow rate	11
7. contamination particulates (size / distribution) gas phase	13
8. Rf power	5
9. handling	14
10. effluents	12
11. time interval	15
12. magnetic field measurements	4
13. end-point distribution emission / coherence shift & composition	6
14. chemical composition liquid & solid (excluding gases)	2
15. stress & strain	1
16. in-line electrical test resistivity	1

Source: See Appendix A, Table A.1.

The Semiconductor Industry

The "semiconductor industry", for the purposes of this study, includes manufacturers of semiconductor devices, suppliers of semiconductor equipment and materials, and providers of analytical lab services.

Three segments usually considered part of the industry's infrastructure were excluded from our definition of the semiconductor industry. First, we excluded all materials suppliers' metrology investments prior to delivery of consumables to the wafer manufacturer facility (i.e., costs outside the wafer fab "barrier" or boundary in order to define a practical limit on the investments included and excluded. Second, after discussions with NIST, we excluded semiconductor-related activities of the federal labs, including NIST. And, third, we excluded universities.[15]

"U.S. Base" of Metrology Costs

As indicated in the introduction, NIST's mission is to support U.S. industry. Therefore, we sought to measure the size of the U.S. metrology industry infrastructure, which we defined as U.S. metrology-supplying firms. It is difficult, in practice, to precisely identify metrology costs incurred only by U.S. semiconductor companies or only by U.S. semiconductor companies in their U.S. operations. It is equally difficult to identify metrology costs just for the U.S. market (which would cover all semiconductor operations located in the U.S. regardless of ownership).

[15] In practice, metrology investment by federal labs, NIST, and universities is reflected in the total cost data we report in Section III because we did not attempt to net their purchases out of the total metrology spending data.

Either way we define the U.S. “base” of metrology costs – that is, either by referencing metrology consuming firms or metrology supplying firms – it is not the same as measuring the size of the U.S. metrology market. We can identify U.S. semiconductor industry consumption of metrology capability wherever it occurs in the world. Using the U.S.-headquartered device producer Texas Instruments (“TI”) as an example, we would include TI’s investment in metrology in its Japanese and Italian operations in our U.S. base number. Alternatively, we can identify the U.S. base of metrology supply as the total for metrology equipment supplied to the world by U.S.-headquartered suppliers, that is, U.S. demand plus exports.

Because we can most reliably measure total metrology supply for U.S.-headquartered firms and foreign affiliates – the “U.S. base” of total metrology supply – we use this definition when we apply a ‘supply side’ method to estimate U.S. metrology-related investment. This definition was also selected because it most closely approximates the metrology “market” for NIST’s semiconductor industry-related services and research results.

Metrology-Related End-Use Segments (or “Cost Centers”)

The “demand side” approach to determining the total size of the metrology infrastructure supporting the semiconductor industry relies on data developed for the four segments of the semiconductor industry that are metrology intensive. We use the term “metrology-related end-use segments or “cost centers” to refer to the metrology-intensive segments of the semiconductor industry's food chain where metrology costs are relatively the most important. The four end-use segments are: wafer fabs (including clean room, clean room shell, and structure)[16], analytical labs (both captive and independent)[17], semiconductor equipment manufacturing (metrology capability embedded in original equipment, metrology costs in tool manufacturing and metrology costs associated with tool development), and consumables delivery systems to wafer fabs (for gases, de-ionized water, and chemicals). See Figure 1.

- Wafer manufacturing or wafer fab refers to the wafer fabrication structure, clean room shell, and clean room. Excluded from the scope of the facilities definition are installed process equipment and consumables delivery systems because these are covered under the semiconductor equipment and consumables cost centers, respectively.

- The semiconductor equipment industry is both a source of demand for metrology capabilities and analytical lab services as well as a supplier of metrology equipment to the semiconductor industry. In developing our estimate of aggregate size of the Metrology-Capability Supplying ("MCS") industry, we separate wafer process tools from the general category of wafer fabrication tools. Wafer process tools include film thickness instruments, microscopes (scanning electron microscopy or "SEM" and AFMS), and wafer defect inspection tools. To be clear, we *do* include process metrology tools in our evaluation, but we report this segment separately to provide NIST with an understanding of the amount of metrology costs related to the other MCS industry segments. Semiconductor equipment-related metrology costs fall into two broad categories: metrology costs embedded in a tool (e.g., a temperature measurement instrument) and spending on metrology capabilities during tool development.[18] See Figure 2. This second category can be further subdivided into

[16] Metrology investments associated with pilot production lines are included as part of front-end facilities investment.

[17] "Captive" means the lab is an internal facility that almost exclusively supports a semiconductor producer's in-house requirements.

[18] Embedded metrology costs can be further categorized as either related to monitoring tool performance or measuring product quality. We did not attempt to provide data at this level of detail.

metrology instruments/equipment purchased for tool characterization and analytical lab services. Analytical lab services are mainly purchased from independent companies, although several of the larger equipment companies have in-house labs.

- Consumable delivery system metrology costs start “inside the barrier” – that is, after the point of delivery to a wafer fab site. See Figure 3. These costs fall into two categories. The first category is in-line monitoring equipment and instrument costs. The second category is off-line analytic lab costs (whether associated with a captive or an independent lab). Consumables suppliers’ metrology-related investments at their production facilities are excluded from the scope of the study in order to define a practical limit to the coverage of metrology costs.

- Analytical labs come in three flavors: in-house labs located inside or adjacent to a clean room facility, in-house, stand-alone facilities (frequently co-located with a company’s research facility), and independent labs. See Figure 4. After extensive discussions with experts familiar with the activities of analytical labs, we concluded that we could not expect to develop reliable survey data about either device companies’ captive labs or independent labs. Captive labs typically do not report to a single cost center, therefore, sources of information about a company’s labs are diffused. We determined that companies would be hesitant to undertake the extensive effort required to provide data for all of their labs. Similarly, all of the independent labs are privately held; information on their activities would be equally difficult to obtain. Therefore, we determined that we would use other means to measure metrology-related investments at these facilities. Again, as noted above, we are measuring spending for metrology-related instruments and equipment, not operating costs.

We measure gas, chemical and water delivery systems metrology-related costs “inside the barrier” of the wafer fab, that is, at the customer site. As stated above, all upstream metrology-related investment costs are excluded. We also excluded all metrology-related investments by raw silicon wafer suppliers because we were unable to obtain reliable information.[19]

[19] This problem arose, in part, because nearly all of the major wafer suppliers are foreign headquartered.

Several other segments of the semiconductor manufacturing sequence were excluded, in particular, assembly (including packaging) because based on our interviews, they were judged to be less metrology intensive or related to final electrical test which is outside the scope of the study.

The demand-side valuation of the size of the metrology infrastructure estimates the amounts of metrology-related spending for each metrology cost center and totals them to arrive at the estimate for the total industry.

C. Measuring Metrology-Related Costs

We have specified “metrology-related costs” as the value of current period spending by the semiconductor industry to acquire “metrology capability.” We begin with a discussion of “metrology capabilities” and then more precisely define metrology-related costs.

Metrology-Related Capabilities

“Metrology-related capabilities” is defined as the semiconductor industry’s acquisition of the means to carry out both in-line and off-line metrology functions related to physical measurements. “Capability” refers to the semiconductor industry’s spending to acquire metrology-related equipment, instruments, systems, sub-assemblies, and components, but it excludes metrology-related operating costs at any level of the semiconductor industry associated with actually taking measurements or providing related analytical lab services.[20]

Metrology-Related Costs

Measuring semiconductor industry “metrology-related costs” is the central objective of this study. Developing reliable data on metrology-related costs in the semiconductor industry is not an easy task. First, as already explained above, we found that we could not apply an “off-the-shelf” definition of metrology. Interviews with experts familiar with metrology requirements in the semiconductor industry led us to define particular metrology activities that, in turn, generated cost requirements throughout the industry. Second, we could not go to a single set of firms at a particular level in the semiconductor industry, say device manufacturers, and collect all the cost information required. Manufacturers of semiconductor devices would not know the amount of metrology costs in other segments of the semiconductor industry’s food chain. Hence, we needed a consistent methodology that allowed identification of metrology costs in all segments of the industry. Third, based on our experience in the industry, we knew that metrology-related cost data was not easily split out in a firm’s cost accounting system. These costs tend to be a fraction of the total cost for a system or structure. This meant we could not rely on a survey of device companies to yield

[20] We should again be clear that analytic lab service firms and in-house organizations, to the degree their activities relate to the semiconductor industry, fall within the scope of our definition for the semiconductor industry. Metrology equipment purchased by analytical lab service firms is included in the definition of the semiconductor industry’s metrology investments, but we do not include lab operating expenses.

reliable results, assuming that they would have completed the survey form. We relied, instead, on experts' judgements to develop ranges for these costs for each metrology cost center. Fourth, metrology costs as a percent of total semiconductor production costs tend to vary significantly over time at a particular facility. Metrology costs are relatively more important during the ramping of a new manufacturing facility when new process steps require full characterization but diminish rapidly as production volumes build and manufacturing processes stabilize. Because we provide only annual estimates that aggregate across all facilities' metrology-related spending, the growth and decay of metrology costs relative to total manufacturing costs evident at a particular facility will not be observable in the aggregated annual results. All of these considerations influenced how we decided to define metrology-related costs.

> ***Metrology-related costs in this study are the semiconductor industry's spending to acquire metrology capability to perform 'physical measurements'.***

Except where expressly stated, we do not include operating expenses associated with performing physical measurements in our definition of metrology-related costs. A current period total cost figure for total metrology costs would include the amortization expense for metrology equipment plus period operating costs and various overhead cost allocations. This approach would be the correct way to determine total metrology-related costs if we were seeking to determine the portion of total finished wafer cost represented by metrology.[21] This definition would not, however, correctly value the size of the U.S.- based, metrology-supplying industry consistent with the objective of our study.

It is useful to reiterate that we *do include* in the scope of the study analytical labs' current period spending for new metrology equipment and instrumentation but *exclude* costs for analytical lab services.[22]

D. Metrology-Capability Supplying Industry

Firms who supply the semiconductor industry with both complete metrology tools and instruments as well as intermediate assemblies and specialized components for metrology systems comprise the Metrology Capability Supplying industry and form the infrastructure that supports the semiconductor industry.[23]

Section III explains how we measured the U.S.-based MCS industry.

[21] This issue is discussed in Section III.

[22] Another reason to exclude operating costs is simply the difficulty we encountered in obtaining meaningful estimates for them. All of the independent analytical labs are privately held and unwilling to provide detailed cost information. Likewise, detailed cost data for in-house analytical lab costs were considered to be sensitive information.

[23] The MCS industry and semiconductor industry definitions are not mutually exclusive since some firms included in the MCS industry are also included in the scope of the semiconductor industry. For example, KLA falls within the parameters of both.

E. Summary of Study Objective

We can state the study's objective by using the definitions that frame the study's scope.

The semiconductor industry – device companies plus selected portions of the industry's infrastructure – has four segments that utilize physical measurements relatively intensively: wafer fabrication, inside the barrier consumable delivery systems, semiconductor equipment manufacturers (embedded costs, manufacturing-related costs, and development-related costs), and analytical labs (both captive and independent).

This study determines the semiconductor industry's metrology costs in two ways. First, we determine the costs from *the supply side* by aggregating the metrology-related revenues of the U.S.-based MCS industry. Second, we estimate total metrology costs from the *demand side* by estimating metrology-related costs for each of the four metrology-intensive segments. Estimates are prepared for 1990 and 1996 with a projection to 2001. See Figure 5.

III. Determining Metrology-Related Costs for the Semiconductor Industry

This section provides our estimate of aggregate metrology-related costs for the semiconductor industry using two approaches. The first approach is a *supply side* method that estimates the size of the MCS industry using company data. The second approach is *demand side*: it evaluates metrology costs for each metrology-intensive cost center and aggregates the cost center data to determine total metrology-related costs. The summary section provides an overview of the results.

A. Determining the Size of the U.S.-Based MCS Industry – Supply Side

This part discusses how we determined the size of the U.S. MCS industry using company data. The first step was to identify firms in the MCS industry. To do this we relied on information developed during our interviews. We asked all of the individuals interviewed to identify the leading companies who supplied metrology capability to the semiconductor industry. Companies identified from the interviews formed our preliminary list of MCS industry companies. To obtain a broad census of companies in the MCS industry, we used the membership directory of Semiconductor Equipment and Materials International ("SEMI").[24] Our judgement was that SEMI's membership list

[24] According to the Semiconductor Equipment and Materials International ("SEMI") web site: "[SEMI] is an international trade association that represents semiconductor and flat panel display equipment and materials suppliers. Founded in 1970 in the United States, SEMI has evolved into an international organization committed to free trade and open markets. SEMI's primary goal is to help its members expand their global marketing opportunities and improve access to their customers and industry, government and civil leaders. SEMI has more than 2,000 member companies located in North America, Asia and Europe. Their products and services contribute more than $55 billion to the world economy. Success in the semiconductor industry typically requires an international effort. SEMI members that market products and serve customers worldwide often rely on the local expertise of SEMI employees at

of nearly 2,000 companies would include nearly all of the companies that we consider to fall within the scope of the MCS industry.[25] Since our interviewees identified the major firms in the MCS industry, we believe that between our preliminary list and the SEMI directory we could identify nearly every significant MCS industry member. The SEMI directory provided other data such as a company's semiconductor-only revenues. This information is extremely useful since many of the larger MCS industry firms supply other end-markets.

The SEMI directory identifies over 300 possible product and application categories for the semiconductor equipment and materials industry (including flat-panel displays). An individual SEMI member will appear in as many product categories as appropriate to cover all its product offerings. We took our preliminary list of MCS companies obtained from our interviews and mapped it into the SEMI product categories. That is, we determined the product categories that included nearly all of the firms from our preliminary list. This exercise identified 20 SEMI product categories, out of 300 total, that constituted the product categories for the MCS industry.[26] See Appendix B. Companies listed in the SEMI directory under each of these 20 category

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these offices."

[25] SEMI annually publishes a membership directory. We used the 1997-1998 directory.

[26] SEMI categorizes all 1,850 of its corporate members in the 1997-1998 directory by a general product description, further broken down by specific type of product and service. For example, the product description category "Analysis/Measurement" is further divided into 12 sub-categories: auger, defect detection, electrical test, ESCA, film thickness, microscopes, probe stations/materials, probing equipment/accessories, SEM, SIMS, surface inspection/flatness, and X-ray. Our 20 categories are taken from more than 300 potential sub-categories.

headings constituted the potential set of firms providing metrology-related capabilities to the semiconductor industry. Further screening of the SEMI companies was required to determine the U.S.-based MCS industry companies.

Using SEMI's 1997/98 Directory, we identified nearly 1,700 entities that fell into the 20 categories. We use the term "entities" to denote the fact that a single company may appear in multiple product categories. We aggregated the separate entities by their common parent reducing the nearly 1,700 entities to 643 companies, both U.S.-based and non-U.S.-based. To obtain a list of companies who manufacture and market metrology-related equipment, we eliminated companies who had no U.S. sales presence (that is, they only supplied metrology capability to offshore locations) or were purely sales representatives or distributors. This reduced the total to 385 companies. This set includes foreign-headquartered companies who supply equipment to the U.S. market.

An inspection of the 385 companies indicated we had not eliminated all of the non-manufacturing companies. To further screen out the non-manufacturing companies, we reviewed detailed company descriptions provided in the "SEMICON WEST 97 Program Directory and Product Guide."[27] We selected this resource because it was very current and provided details on a company's functions. For example, a significant number of companies eliminated at this screening were suppliers of

[27] SEMICON WEST is the largest semiconductor equipment and materials supplier tradeshow in the U.S. The tradeshow directory lists participants and provides company descriptions.

assembly and electrical test equipment; metrology was only a very minor part of their business. We also removed companies whose principal line of business was analytical laboratory services. We discuss these firms below. This additional screening left 258 companies.[28] We then removed 59 non-U.S.-headquartered companies leaving a total of 199 U.S.-headquartered companies that represent the U.S. base of metrology-capability suppliers. We further refined the list separating 22 companies who supplied process monitoring equipment[29] and removing from the list another 8 companies that had no reported sales data. This left 169 companies.

> ***We define the total sales of these 169 companies together with the 22 process monitoring companies to be the value of the U.S. base of metrology capability suppliers.[30]***

Sales data for 1996 was obtained from the SEMI directory and supplemented by company 10-K information if a company was publicly-held.[31]

We needed to make one adjustment to the reported sales data contained in the SEMI directory. SEMI reports the range for semiconductor-related sales for all categories of semiconductor products a company sells, not just metrology. We had to

[28] We randomly selected 80 companies from this list – about 25% of the total – and conducted an additional review to confirm that we had correctly identified the functions they performed. This additional review relied mainly on information provided in a company's internet web site.

[29] This set is U.S.-headquartered only. There are major non-U.S. process monitoring equipment suppliers who were already removed from the list.

[30] Total metrology equipment costs would need to account for the process monitoring equipment costs.

[31] The SEMI directory reports a range for a company's semiconductor-only revenues. We took the mid-point of the range except for larger companies where we were able to obtain actual revenue data using 10-K information or other sources.

estimate the metrology-only portion of total semiconductor sales. Fortunately, a large portion of the MCS companies only sell metrology-related products and no adjustment was needed. Further, we were able to confirm metrology-only sales for many of the larger MCS companies using other sources. This left about 50 mid-sized MCS companies with semiconductor-related revenues in the range of $15 million to $100 million for whom we needed to estimate the portion of their total sales related to metrology. After evaluating several methods to accomplish this adjustment, we decided the best method was to assume that between 40% and 60% of their total semiconductor-revenues were metrology-related. This range was determined by inspecting the mix of products sold by these firms. Most of the mid-sized firms had a relatively large portion of their product categories related to metrology, hence we felt it was reasonable to infer that a substantial portion of their revenues related to metrology products. We concluded that applying a range of around 50% of total sales was a reasonable way to estimate this adjustment for these 50 firms.

To determine the size of the U.S. base of MCS companies for 1990, we compared the list of 169 companies with the SEMI 1990 Directory and identified 71 matches. We determined the 1990 metrology-related revenues for these 71 companies.[32] Appendix E provides the list of U.S.-based metrology capability

[32] There are companies who may have exited the business after 1991 in which case we would not have identified them. We do not believe this number is significant. Similarly, there may have been companies who were acquired or merged after 1991; again we would not have identified them either. We did attempt to verify how many companies were acquired. Our preliminary indication was that the number was small. Still, there is a likelihood that we are understating the true amount of metrology costs for 1990. The fact that both the demand and supply-side methods yield consistent results for the growth of the industry between 1990 and 1996 supports our conclusion that our understatement of 1990 metrology costs is not

companies, U.S.-based process monitoring equipment companies, companies excluded due to lack of data, and foreign companies, including foreign-based process monitoring companies.

Results of Applying the Supply-Side Method

We estimate, based on our supply-side methodology, that the size of the U.S.-based MCS industry, measured by revenues, ranged between $1,980 million and $2,300 million in 1996.

This total includes wafer process equipment suppliers identified as U.S.-based MCS companies in 1996. We estimate that the U.S.-based MCS industry was $520 million in 1990 on the same basis. These results indicate that the MCS industry grew by over 400% between 1990 and 1996 or at a compound annual growth rate ("CAGR") of between 22.3% and 28.1%. Net of process monitoring equipment, the size of the U.S.-based MCS industry was estimated to be between $1,080 million and $1,400 million in 1996 versus $275 million in 1990 – an increase of 450% or a CAGR of 25.6% to 31.1%.

If foreign-headquartered company sales are added to the U.S.-based MCS industry (U.S.-based entity revenues plus sales of foreign entities in the U.S.), the size of the U.S. MCS market is estimated to be $750 million in 1990 increasing to between $2,525 million and $2,845 million in 1996.

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significant.

Table 2 Supply-Side Estimate of Total U.S. Metrology-Related Costs ($ Million, except where noted otherwise)			
	1990	1996	
		Low Estimate	High Estimate
Metrology Process Tool Suppliers	245	900	
All Other Metrology Suppliers (net of process monitoring equipment)	275	1,080	1,400
U.S.-Based MCS Industry	520	1,980	2,300
Compound Annual Growth Rate		22.3%	28.1%
U.S.-Based MCS Industry + Foreign-Headquartered Sales	750	2,525	2,845

Structure of the MCS Industry

Comparing the data on the number of metrology-capability supplying firms in 1990 versus 1996 suggests a very high rate of entry into the industry during that period: only 71 of the 169 companies present in 1996 could be identified in 1990. While there are other possible explanations for the large difference, we believe there was, in fact, a large number of new firms who commenced supplying metrology-capability to the semiconductor industry between 1990 and 1996. Companies would have been attracted to supply the semiconductor industry in early 1990's because the semiconductor industry experienced continued rapid growth becoming a very large end market. Many firms who previously might have considered the semiconductor industry's requirements too demanding, especially given its relatively small size, became more interested once the semiconductor industry's revenues exceeded $50 billion in 1990 and annual capital spending exceeded $10 billion.

Comparing the structure of the MCS industry between 1990 and 1996, the following changes are evident. As of 1996,118 companies out of the total of 191 had semiconductor-related sales under $8 million; of this total only 45 companies or 38% were identified as supplying the semiconductor industry in 1990. Of the 73 companies with metrology-related revenues $8 million and larger, 52 were identified as having sales to the semiconductor industry in 1990. We can also review changes in the MCS industry by technology segment: 48% of analysis/measurement entities "overlapped" (i.e. 48% of the analysis measurement entities identified for 1996 were also identified as suppliers in 1990), 35% of the gas/water/chemical metrology suppliers overlapped, 42% of the inspection equipment supplying entities overlapped, and 51% of the measurement entities overlapped. That gas/water/chemical metrology-capability suppliers show the greatest degree of new entrants is not surprising based on the changes in the semiconductor customer base and technology. We discuss this point further in the following section.

Excluding process tool companies, comparing the average company metrology-related revenues to the semiconductor industry, 1996 versus 1990, indicates that average company revenues remained relatively small: $7.3 million in 1996 versus $3.4

million in 1990 ($5.4 million for companies who also had sales in 1996).[33] Since a number of companies identified as metrology capable suppliers also sell to other end-markets, this measure does not reflect the average size of the total corporate entity.

B. Determining the Size of the U.S.-Based MCS Industry – Demand Side

This section determines the size of the U.S.-based MCS industry using *a demand-side* methodology. We first review trends in each of the four metrology-related cost centers and then aggregate the amount of metrology spending estimated for each cost center to arrive at an industry total.

Cost Center 1: Wafer Manufacturing Facilities

Metrology costs related to wafer fabrication facilities occur during two stages: facilities construction and facilities operation. Measurements at these two stages involve very different types of activities. Metrology-related activities during facilities design and construction (excluding consumables delivery systems) are relatively minor, although they tend to scale as facilities' costs increase. These activities generally relate to validation of the structure or clean room specifications during construction and final acceptance. Metrology activities during operation are more varied. In the late 1980's when a one-micron capable facility was considered to be a leading edge facility, metrology measurements were based on sampling the major metrology activities

[33] We excluded process tool companies because these tend to be significantly larger in scale, on average, than the average size of the non-process tool supplier.

related to measuring particulates in clean rooms with portable counters and relative humidity with instruments. Today, the trend is towards embedded, in-line process control with constant monitoring.

The following summarizes current measurement activities related to wafer fabs:

- During construction and certification of clean rooms, a series of measurements are required including: (i) airborne particle count (to certify the finished room); (ii) floor vibration, especially with respect to stepper placement, to see if the floor meets the stepper manufacturer's vibration requirements[34]; (iii) room noise, if specified (requires a sensor costing $4K); and (iv) yellow light spectrum, to ensure that lights in the photolithography areas do not emit any portion of the spectrum harmful to the process, namely the shorter wavelengths.

  Effluent monitoring has become more important, especially since 1992 due to changes in federal and state regulations, but its costs are still relatively minor. However, with each location applying different rules and regulations for the discharge into the water and air, monitoring costs vary significantly by location. In Texas, for example, eight years ago fab construction engineers were just starting to think about effluent issues, whereas, in Silicon Valley there was already a major concern about the discharge of organic chemicals. Typically semiconductor firms bear testing costs to validate that a new facility meets federal, state and local discharge regulations at the time a facility is certified. Outside firms qualify the facility. There usually is no requirement to periodically re-qualify. U.S. standards are now becoming the *de facto* world standards since the U.S. is usually considered to have the most stringent regulations and enforcement.

- Once certified, the clean room requires the following metrology equipment to monitor particulates and general cleanliness:

[34] Vibration is principally an issue at the time of equipment installation. Vibration sensitivity specifications typically are provided by the equipment supplier. This is a relatively simple measurement to verify. The actual cost to certify vibration requires a measurement instrument costing between $5K to $10K. The criteria associated with measuring structural and mechanical vibration for structures is in dispute. See K. Medearis, "Rational Vibration and Structural Dynamics Evaluations for Advanced Technology Facilities," *Journal of the Institute of Environmental Studies*, September/October, 1995.

– an airborne particle counter capable of detecting at least 0.10 micron minimum particles with a flow rate of at least 1 CFM, with attachments to the counter to scan filter faces for leaks;

– air velocity measuring equipment capable of reading accurately down to 30 - 40 FPM to monitor vertical laminar flow and other air flows;

– an accurate air temperature and humidity measuring system to verify the HVAC operation[35];

– a low-pressure gauge to monitor internal pressure in the clean room;

– a deep ultra-violet photolithography chemical system sensitive to certain airborne contaminants;

– a system to measure ionization levels or static charge; and,

– safety-related monitoring including fire and toxic gas monitoring.

Certain other measurements are taken off-line, for example, electrostatic discharge.

Metrology used in monitoring systems to control factors such as humidity or air flow is not directly measuring parameters related to wafers being fabricated in the facility. Clean room parameters are monitored via a control system costing between $4 million and $5 million per installation that monitor chilled water delivery, air handling, dew point, steam injection, and auto dampers for pressure. By comparison, for a fab of the late 1980’s, control unit costs would have ranged between $2.5 million and $3 million per installation. An important factor driving the 80% increase in cost per monitoring unit is the need to increase the number of monitoring (or detection) points.

[35] While specifications for temperature and humidity have tightened, the cost of monitoring has remained relatively small because process steps that are sensitive to temperature and humidity are enclosed in special chambers.

This increase was not driven, *per se*, by tighter specifications in the fab design or tighter process specifications. Rather the increase was a result of adding more controls with more process driven systems. For example, regulations implemented in the early 1990's relating to exhaust abatement necessitated greater control over effluents. In addition, as total fab costs (structure plus clean room plus installed equipment) reach $2 billion to $3 billion there is need for redundancy in the systems to ensure continuous operation of the facility. Because control costs are a very minor cost element, it pays to gain redundancy in controller systems to ensure that the systems are robust.

With five to eight fabs constructed in the U.S. in 1996, the total amount invested in monitoring control systems just for new fabs ranged between $20 million and $40 million. Spending on replacement and upgrades for existing fabs is a multiple of the spending on new fabs. The best estimates we obtained from the individuals we interviewed suggested a range of $50 million to $150 million for 1996. In total, therefore, metrology costs for U.S. wafer fab facilities in 1996 were estimated to be in the range of $70 million to $190 million. Spending in 1990 for facilities metrology equipment was estimated to be in the range of $30 million to $90 million.

Cost Center 2: Semiconductor Equipment Manufacturing

There are three categories of metrology-related costs for physical measurement incurred by semiconductor equipment manufacturers: (1) metrology-related costs incurred during new tool development (including the costs associated with using the services of analytical labs); (2) metrology-related costs incurred during tool manufacturing; and (3) metrology-related costs embedded in the tool.[36]

Tool Development Metrology Costs

Metrology-related costs incurred during tool development as a proportion of total R&D costs vary significantly over the development cycle. These costs also vary by the type of semiconductor equipment manufacturer. We obtained data on metrology costs incurred in semiconductor equipment development from a survey of 28 U.S.-headquartered semiconductor equipment manufacturers.[37] Companies were asked to provide data on R&D as a percent of sales in three periods, 1990, 1996, and projected to 2000, as well as the percent of R&D costs related to metrology. See Table 3.

Table 3
% of Total R&D Metrology-Related Costs for U.S. Semiconductor Equipment Companies

Period	Average % of Total R&D Related to Metrology
1990	under 5%
1996	8%
2000	Over 10%

Source: Author's survey of semiconductor equipment companies, 1997.

[36] There are other metrology-related costs that we do not measure. For example, when a new tool is first installed in a fabrication clean room there can be various measurements made.

[37] We sent a survey to 120 U.S.-headquartered semiconductor equipment firms. Approximately 40 firms responded. The respondents accounted for about 80 percent of the total U.S. equipment industry revenues in 1996. This survey was conducted for a different sponsor.

Tool Manufacturing Metrology Costs

In semiconductor equipment manufacturing, for major tool categories, the capital costs to acquire metrology instruments and tools required to support manufacturing, as a percent of equipment company total revenues, are estimated to run around 10% in 1996. If metrology capital costs are amortized over the life of the associated process tools, the depreciation expense ranges between 5% and 7% of total revenues.

If metrology costs are compared to the semiconductor equipment industry's cost of goods sold, metrology costs represent about 10% of the total manufacturing cost of goods sold, including depreciation costs.

Looking ahead, as the semiconductor equipment industry introduces 300mm capable tools, there will be another spike in metrology costs.

Embedded Metrology Costs

The third area of metrology costs related to process equipment is metrology capabilities embedded in process tools. For example, the typical semiconductor resist processing tool requires nine different types of embedded measurements plus off-line measurements as well. (See Table 1 and Table A.1 which summarize the metrology attributes required by each major tool category.) It was very difficult to obtain data on the amount of costs associated with these embedded metrology capabilities. No equipment company keeps records in a manner that would permit it to readily determine its embedded metrology costs. Instead of direct cost data, we have to rely on the opinions provided by several interviewees. Their best estimates indicated that these costs for embedded metrology capability typically run in the 3% to 7% range (expressed as a percent of the total tool price). It was generally believed that these percentages have remained relatively constant over the past five years. Interviewees noted that few customers directly value metrology capabilities and, therefore, would resist increased tool prices to pay for additional metrology capabilities. Further, because costs for embedded metrology-related components are relatively minor relative to other component costs, few tool companies track these costs explicitly. Excluding the potential impact of a move to employ tool-based sensors (mentioned in the introduction), embedded metrology component costs are not expected to increase as a percent of total tool cost.

Total Semiconductor Equipment-Related Metrology Costs

Table 4 tabulates metrology costs related to semiconductor equipment.[38] Metrology costs in the semiconductor equipment segment increased at a rate of 29.2% per annum (CAGR), exceeding the rate of increase in total wafer process equipment revenues, worldwide, of 27% in the same period; the higher rate of growth reflects the increased metrology costs associated with new tool development. See Table 4. Approximately 90% of total metrology costs in the semiconductor equipment cost center relate to metrology costs incurred in tool manufacturing and embedded metrology costs. Based on this analysis, it becomes evident why metrology costs increased in the 1990 to 1996 time frame at nearly the same degree as semiconductor wafer fab equipment revenues since the wafer fab equipment metrology cost center end-use accounts for roughly two-thirds of total metrology equipment, instruments, and sub-systems.

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[38] As with the supply-side estimate, these estimates are for total purchases of metrology capability, regardless of source.

Table 4
Metrology Costs in the Semiconductor Equipment Industry
(Excludes Process Metrology, Test & Assembly Equipment)
($ Millions, except were noted otherwise)

Category	1990	1996	2001Projected
1. Estimated U.S. Base Wafer Process Equipment (see note 1)	2,250	9,400	19,000
Compound Annual Growth Rate		26.9%	15.1%
Semiconductor Equipment Manufacturers' Metrology Costs			
2. Metrology-related costs in R&D	15	90	230
3. Metrology-related costs for tool manufacturing	115 – 160	470 – 660	950 – 1,330
4. Cost related to embedded metrology capability in tools	70 - 160	280 – 660	570 – 1,330
Total (Lines 2 – 4)	190 - 335	840 – 1,410	1,750 – 2,890
Average Compound Annual Growth Rate		27.5%	15.6%
Note 1: Sources include VLSI 1990; Paine Webber 1995 data adjusted by worldwide growth rate of 14% to 1996 level; and DATAQUEST, Dec. 1997 forecast.			

Cost Center 3: Consumables Delivery Systems[39]

We apply a definition used in the semiconductor industry in defining metrology costs related to consumable delivery systems to be covered by this study, namely we include measurement costs at a wafer fab facility that occur inside the “battery limit.” The battery limit defines the boundary of responsibility between a consumables supplier and a semiconductor device company customer with the supplier responsible for product quality up to the battery limit. In practical terms, by applying this definition we have excluded all upstream consumable supplier metrology costs.

Since 1990, there has been a shift in the relative measurement activities and responsibilities between the supplier and the customer. Customers support point-of-use facilities – called Chemical Delivery Units or Modules (“CDUs” or “CDMs”) -- on site at the wafer fab with the suppliers bearing responsibility outside the battery limit. CDU’s are located outside the wafer fab structure but still close enough to avoid a long run to the fab and are segregated into separate bays for safety.

As quality specifications tightened, inside the battery limit metrology costs related to monitoring consumables have risen. Because the semiconductor industry has never been able to validate an absolute value for different types of impurities, the industry simply goes to the limits of detectability. This philosophy is driven by the simple

[39] In addition to information provided in interviews, information in this section is also gathered from the following sources: (1) “Bulk Chemical Delivery: Does It Impact Yield?” *Semiconductor International*, July 1994, pp. 108 - 114; (2) “Chemical Distribution Systems Take the High Road,” *Semiconductor International*, July 1991, pp. 58 - 62; and (3) “Assessing the Design and Performance of a Central Hot Ultrapure Water System,” *Microcontamination*, February 1993, pp. 2 - 64.

economics that with instrumentation costs relatively minor, it pays the fab manager to purchase the best instruments, regardless of the true benefits obtained.

> "We are driven by our customer – the fab operations group – wanting to have major systems free of problems because $200K or $500K, [the cost of monitoring], is a small cost for uncertain benefits – they like to rule out issues."

Complicating the assessment of consumables-related metrology costs is the fact that certain of these measurements really take place in analytical labs and the rising costs for consumables quality control measurements gets reflected in the rising costs at the analytical labs. For example, a fab must periodically perform a trace metals analysis. In the late 1980s, this measurement might have been done once per month at a relatively minor cost of around $25K annually. Now the analysis is done almost weekly with more expensive equipment. Typical costs for the analysis today are around $400K per year per fab site.

Here are other illustrations of changes in consumable delivery system monitoring costs:

- De-ionized ("DI") water systems include analytical instruments used to control and monitor the DI water distribution system. These instruments include Total Oxidizable Carbon ("TOC") monitors, particles, resistivity, silica, and sodium. Costs for DI monitoring approximately doubled in cost between the late 1980s and currently. With between five to eight fabs constructed in the U.S. in 1996, the total amount invested in de-ionized water system monitoring would run around $2 million to $3.2 million, per year.
  - Costs were sensitive to the move from 1 micron to 0.5 micron manufacturing. Instrumentation requirements changed due to the need for increased sensitivity to achieve more accurate detection limits. The 1 micron fab cost for instrumentation was $100K around 1990; now the investment per fab would typically run in the range of $250K to $1,000K, with $400K the average. The average cost is expected to increase to around $500K to $750K with the next generation of fabs.

- There are no barriers in the measurement area to move into sub-micron manufacturing, though these monitoring costs would be expected to increase by 2X or more from current cost levels.

- Bulk gas monitoring focuses on hydrocarbon levels in oxygen and nitrogen tanks. Moisture is not always measured (some companies do it, others do not). This is a one-time test at the time a new system is brought on line. Main trunk lines to fab are verified with off-line testing. Typically inside the barrier there is no testing of the bulk gas lines for particulates; this is the responsibility of the supplier.

  - On-line measurement costs for bulk gas delivery are relatively minor, costing $70K for system in 1990 and currently $90K. Cost is more a function of the size of the system (number of tanks monitored).

- Other delivery systems involve relatively minor costs. Specialty gases are corrosive so typically once a specialty gas line is installed they clean well and do not require continuous monitoring. Liquid chemicals require a relatively minor amount of monitoring for particulates. Currently, this is an outside the barrier responsibility of the suppliers who certify each delivery's purity levels.

- Chemical Mechanical Polishing ("CMP") has led to a major new set of requirements for monitoring. These tools require a slurry dispenser station that uses a monitoring instrument costing around $50K to $70K. Slurry effluents will also require monitoring in the future as new, non-benign slurries are utilized.

Metrology costs associated with all phases of consumable delivery systems inside the barrier, both for new facilities and upgrades, for 1996 are estimated to range between $100 million and $300 million.

Cost Center 4: Analytical Labs

Analytical labs associated with the semiconductor industry can be divided into captive and independent labs. There are an estimated 100 independent organizations that perform analytical lab functions for the semiconductor industry, but the vast majority of these independent labs perform tests as a secondary activity and many perform only very specialized tests. In some instances, semiconductor equipment companies perform specific measurements to characterize their equipment. Of the 100 firms, three of the largest firms that are dedicated to providing analytical lab services are Balazs Analytical Laboratory, Charles Evans & Associates, and Surface Science Laboratories.

In-house analytical labs come in a variety of forms.[40] Some analytical labs are stand-alone, others are part of either an R&D lab or an R&D prototype line. In the semiconductor industry an increasingly popular concept is the "fab lab," an analytical lab co-located with a clean room, frequently with one window looking into the clean room. Fab labs are most common with the largest semiconductor makers at their larger, full-volume manufacturing sites. Tools typically procured for the fab lab include the following: SEM equipped with energy dispersive spectroscopy (EDS), focused ion beam systems (FIB), whole wafer Auger microscopes, whole wafer time of flight (ToF), secondary ion mass spectrometry (SIMS), dynamic SIMS, atomic force microscopy (AFM), total reflection x-ray fluorescence (TSRF), transmission electron microscopy (TEM), ellipsometers, x-ray fluorescence (XRF) equipment, and fourier transform infrared (FT-IR) spectrometers.

In 1996, the total semiconductor-related sales of the three independent analytical labs totaled approximately $20 million. Discussions with experts suggest that the total analytical lab revenues associated with the supply of services to the semiconductor industry would likely range in the $50 million to $100 million range. If correct, then

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[40] The discussion in this section is based, in part, on A. Diebold and R. McDonald, "The At-Line Characterization Laboratory of the 90s." *Future Fab International,* 1997.

independent analytical lab procurement of metrology equipment and instruments allocated to support the semiconductor industry would range between $5 million and $15 million.

Turning to the in-house labs, according to one estimate, the typical fab lab installation costs between $10 million and $15 million to equip.[41] By comparison, a fab lab, vintage 1990, would have cost approximately $2 million to fully equip. With between 5 and 8 new fabs constructed in 1996, this suggests total new fab lab equipment costs in the range of $50 million to $120 million. Additions and upgrades to existing fab labs would likely double this figure, suggesting that in-house procurement of metrology equipment is significantly greater than independent analytical operations. (These costs exclude the cost of the clean room space.) We estimate that total spending for in-house analytical lab equipment, including new installations, probably is between $100 million and $300 million.

[41] Diebold and McDonald.

C. Demand Side Estimate

Table 5 summarizes the results of the demand side analysis.

Estimated 1990 total metrology-related spending by the four cost centers ranged between $330 million and $625 million. The 1996 metrology-related spending was estimated to range between $1,165 million and $2,265 million. The implied rate of growth between 1990 and 1996 for total metrology-related spending was 24.4% (using the mid-point of the 1990 and 1996 ranges). Semiconductor equipment accounted for nearly two-thirds of total metrology costs in 1996. The growth of metrology costs in this segment closely tracked the growth of size of the total wafer fab equipment market.

That semiconductor equipment growth drives MCS industry growth is not surprising since a substantial portion of metrology cost is incurred in semiconductor equipment manufacturing and is also embedded in final wafer process tools. The fastest growing metrology cost segment is analytical labs. This fact probably reflects the rapid expansion of in-house labs, especially fab labs.

Table 5 Demand-Side Estimate of Total U.S. Metrology-Related Costs ($ Million, except where noted otherwise)						
Metrology End-Use Segment	1990 Range		1996 Range		% of Total Spending (1996)	Compound Annual Growth Rate (on median of range)
Wafer Fab	45	90	70	190	7.6%	11%
Semiconductor Equipment, (Note 1)	190	335	840	1,410	65.6%	27%
Consumables Delivery Systems	75	150	150	350	14.6%	14%
Analytical Labs	20	50	105	315	12.2%	35%
Total U.S. Metrology-Related Costs	330	625	1,165	2,265	100%	24.4%
Note 1: Includes metrology-related costs embedded in final equipment plus metrology-related costs in R&D and manufacturing.						

D. Size of the Metrology Infrastructure in 2001

On a global basis, the semiconductor industry is projected by DATAQUEST, a market research firm that follows the semiconductor industry, to grow at a CAGR of 16.2% between 1996 and 2001. DATAQUEST also projects semiconductor-related capital spending to increase at a CAGR of 13.3% and wafer fab-related capital equipment sales to increase at a CAGR of 15.5%.[42] The World Semiconductor Trade Statistics program projects the U.S. semiconductor market to grow at a CAGR of 17.7% between 1996 and 2000.

Historically, metrology-related spending growth has followed the general trend of semiconductor industry capital spending and, in particular, wafer fabrication equipment revenues. The close link to the growth in wafer fab revenues is explained by the fact that over 60% of metrology-capability equipment is consumed by the wafer fab equipment end market. As indicated in Table 6, metrology costs in the semiconductor equipment cost center are projected to rise by 15.5% CAGR between 1996 and 2001 based on the DATAQUEST forecast for the wafer fab end market.

> ***Assuming metrology costs in the other cost centers growth at roughly the same rate, the total size of the metrology infrastructure would increase to between $5.2 billion and $5.9 billion by 2001, based on the supply side definition of the total U.S. base of metrology spending. Using the mid-point of this range, the size of U.S. metrology infrastructure should reach $5.5 billion by 2001.***

[42] DATAQUEST as cited in *Channel*, January 1998, page 7.

IV. Summary

We can compare the results obtained from the supply side evaluation to the results from applying the demand side method. In making this comparison it is important to understand that the two methods were applied to different definitions for the semiconductor industry. The supply side approach covers metrology-related sales for the entire semiconductor industry, not just the four cost intensive segments. We determined sales data for U.S.-based MCS companies and then added sales by foreign-headquartered companies to arrive at a total. The demand side approach covers just the four metrology-intensive segments and implicitly includes U.S.-source as well as foreign-source metrology hardware. Given these differences, the most appropriate level to make the comparison would be the supply side total, U.S.-based MCS industry *plus* foreign-headquartered company sales in the U.S. market, to the total demand side result. Because the former approach covers the entire semiconductor market, we expect the supply side result to be greater than the demand side one.

Table 6 summarizes the overall results from the two methods and provides a comparison of the metrology spending levels and growth to those for the world semiconductor industry and semiconductor equipment industry.

Table 6
Comparison of Trends in Estimated Total Metrology-Related Costs to World Semiconductor Industry Revenues, 1990, 1996 and 2001
($ Million, except where noted otherwise)

Segment	1990 Low	1990 High	1996 Low	1996 High	2001	CAGR % 1990 to 1996	CAGR % 1996 to 2001
	Supply-Side Estimate (includes non-U.S. sources) ($Million)						
Total U.S. Metrology-Related Costs (Note 1)	750		2,525	2,845	5,500	25.2%	15.5%
	Demand-Side Estimate ($ Million)						
U.S. Metrology Costs (total all end-use segments)	330	625	1,165	2,265	3,500	24.4%	15.5%
	World Semiconductor Industry ($ Billion)						
Revenues (Note 2)	50.5		129.2		270.0	17.0%	16.2%
Capital Expenditures (Note 3)	13.8		45.0		84.0	21.8%	13.3%
Wafer Fab Equipment Expenditures (Note 4)	5.7		21.7		44.5	25.0%	15.5%

Notes:
(1) Includes foreign-headquartered metrology suppliers' U.S. sales.
(2) Semiconductor Industry Association
(3) DATAQUEST, December 1997 (*Channel*, January 1998, page 7.)
(4) DATAQUEST and Paine Webber. Includes metrology process tool revenues.

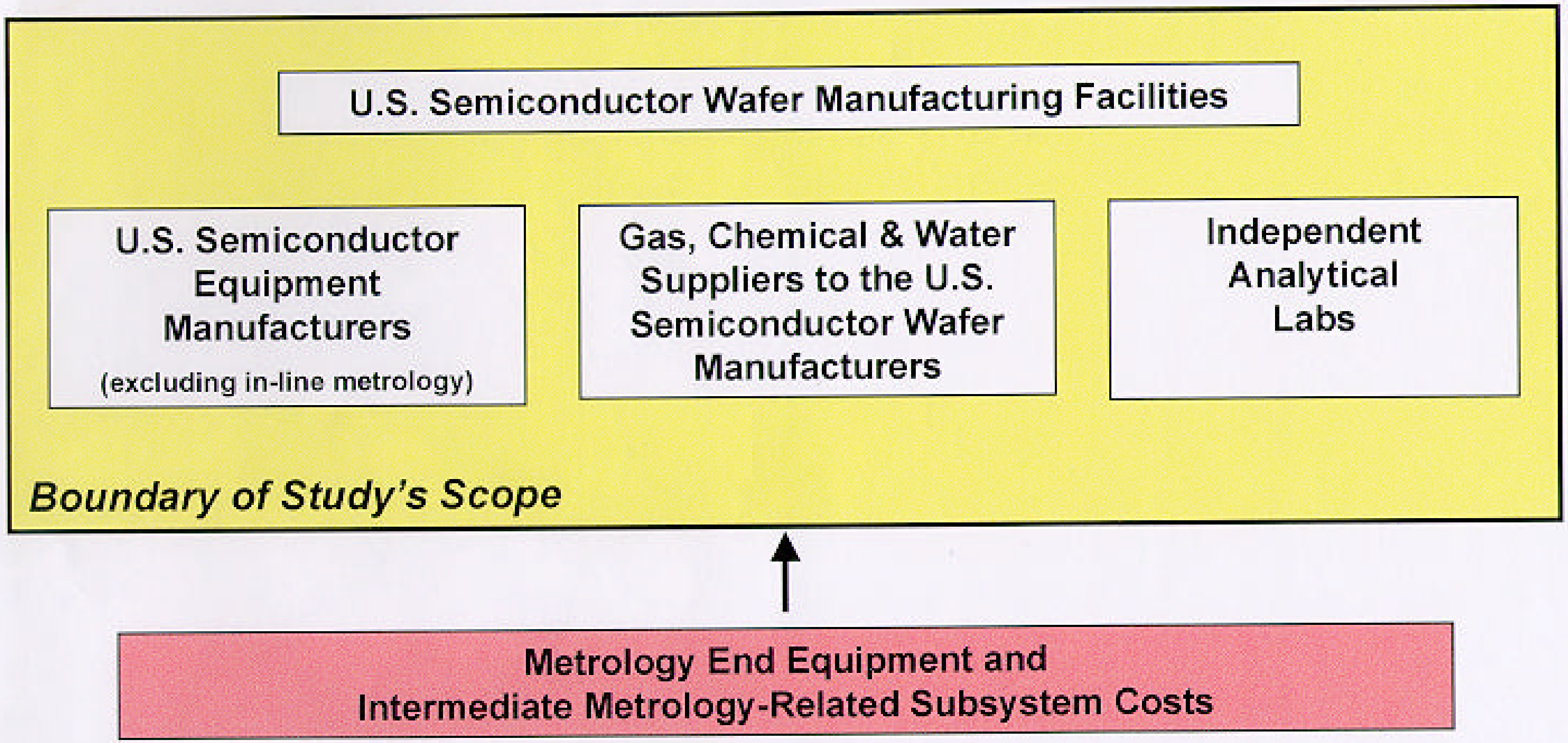
We conclude by commenting about the accuracy of our estimates for the size of the U.S. metrology infrastructure.

Both the supply side and demand side estimates yielded consistent results for the rate of growth of the metrology infrastructure. Where the results are less certain is the industry's size. This should not be surprising given the difficulties we encountered, explained at length in Section II, in defining the metrology infrastructure. Both the supply side and the demand side methods yielded a fairly wide estimated range for the size of the metrology infrastructure. For 1996, the ratio of the maximum to the minimum estimated size was nearly 2X for the supply side method and 1.5X for the demand side. However, the supply side and demand side ranges do not overlap. Our interpretation of this result is that the best estimate for the industry's size in 1996 is a range constructed from the high end of the demand side estimate and the low end of the supply estimate. We believe our approach is reasonable for the following reason. The supply-side method overstates semiconductor industry metrology costs because it requires the estimation of both non-metrology sales of U.S. metrology suppliers and the division between U.S. and non-U.S. sales. On the other hand, we concluded that the demand-side method understates total metrology costs because it relies mainly on experts' estimates of metrology costs for certain end-use segments. This meant that it was more prone to underestimation due to differing definitions and incomplete knowledge about the true extent of metrology spending in the semiconductor industry.

We believe the most reliable estimate for the metrology infrastructure's size would be between $625 million $750 million in 1990, between $2.3 billion and $2.5 billion in 1996, with expected growth to between $3.5 billion and $5.5 billion by 2001.

Figure 1

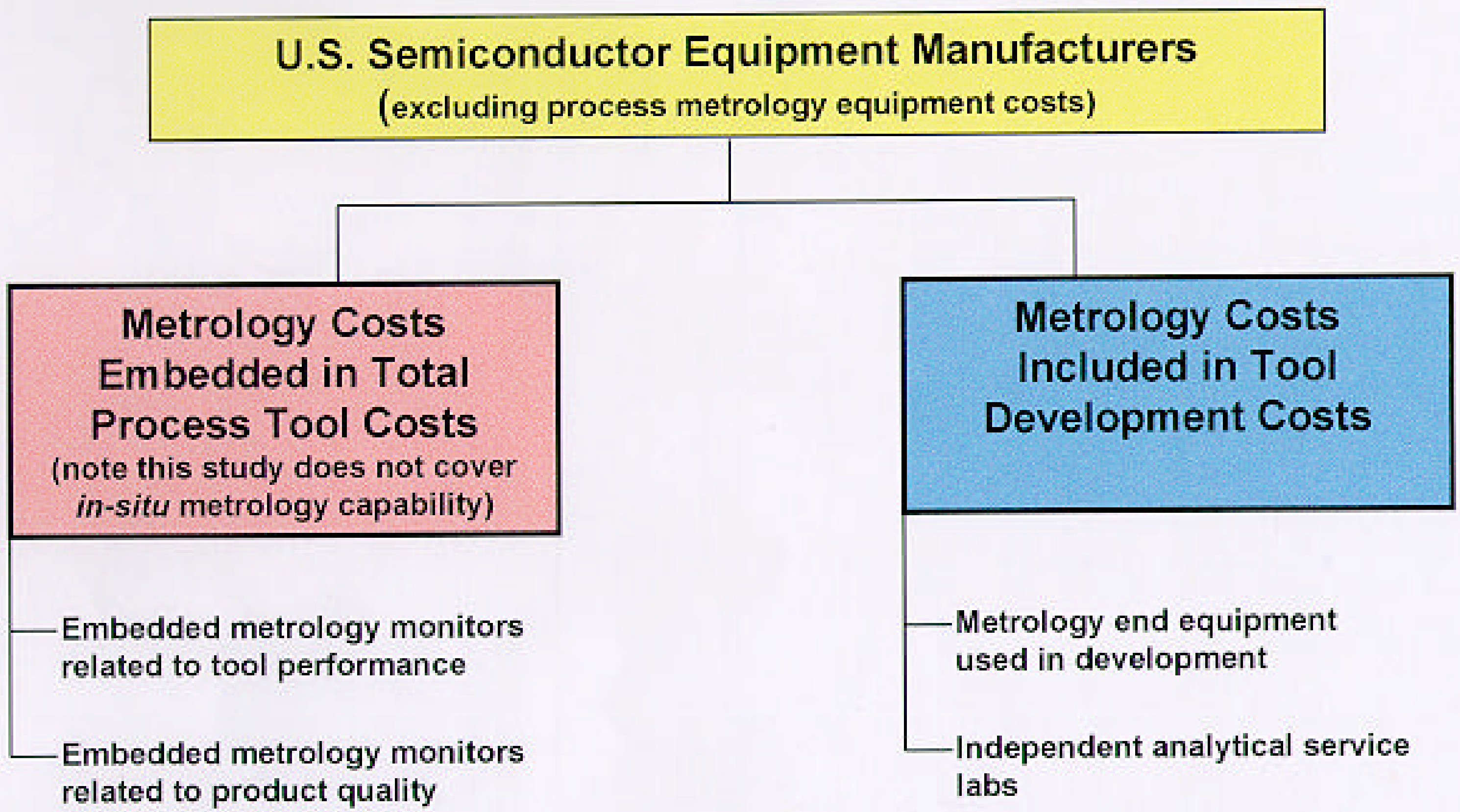
Overview of Scope of Metrology Costs Covered by this Study



Technecon Analytic Research

Figure 2

Semiconductor Equipment Metrology Costs Included in the Scope of this Study



Technecon Analytic Research

Figure 3

Gas, Chemical and Water Supply Metrology Costs

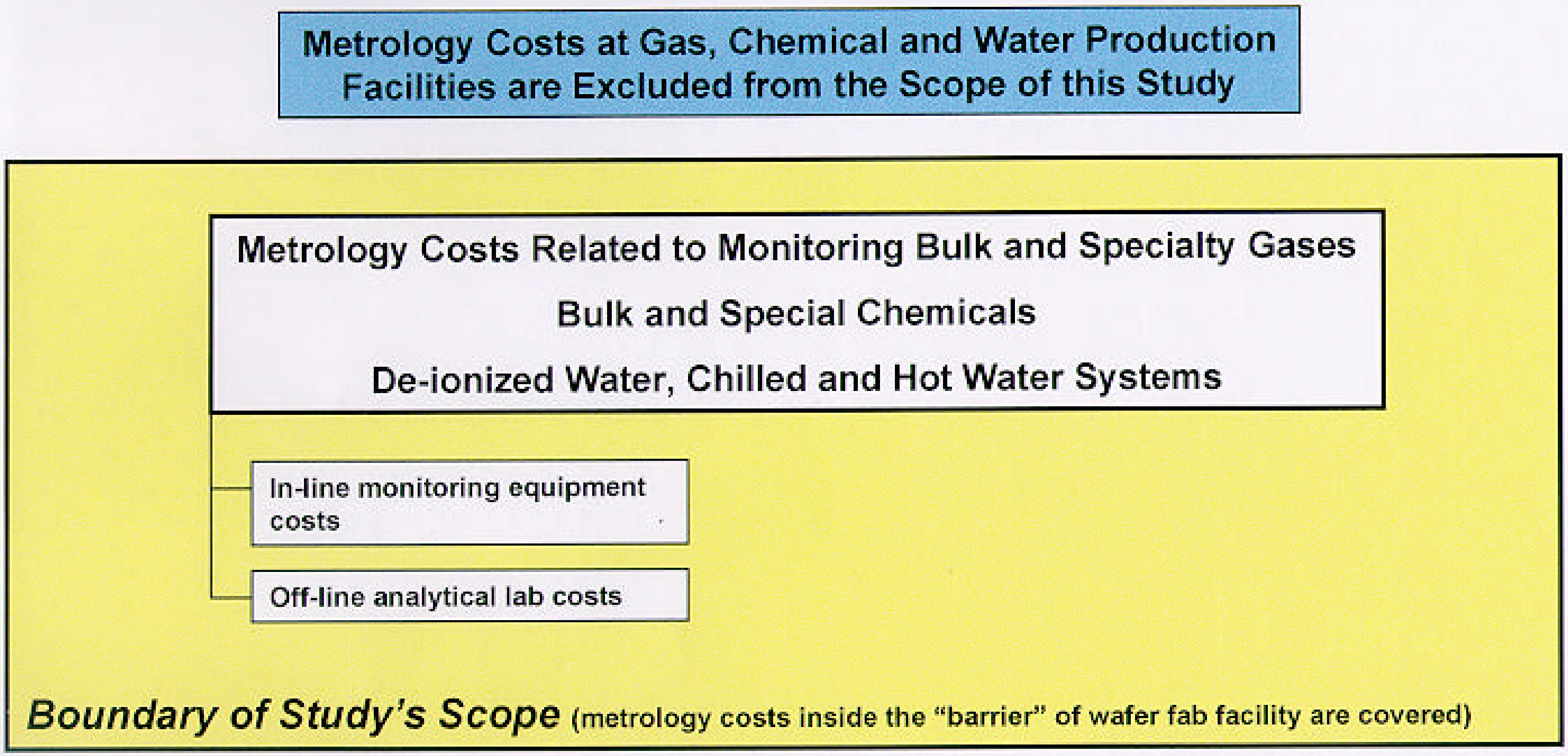


Figure 4

Three Types of Analytical Labs

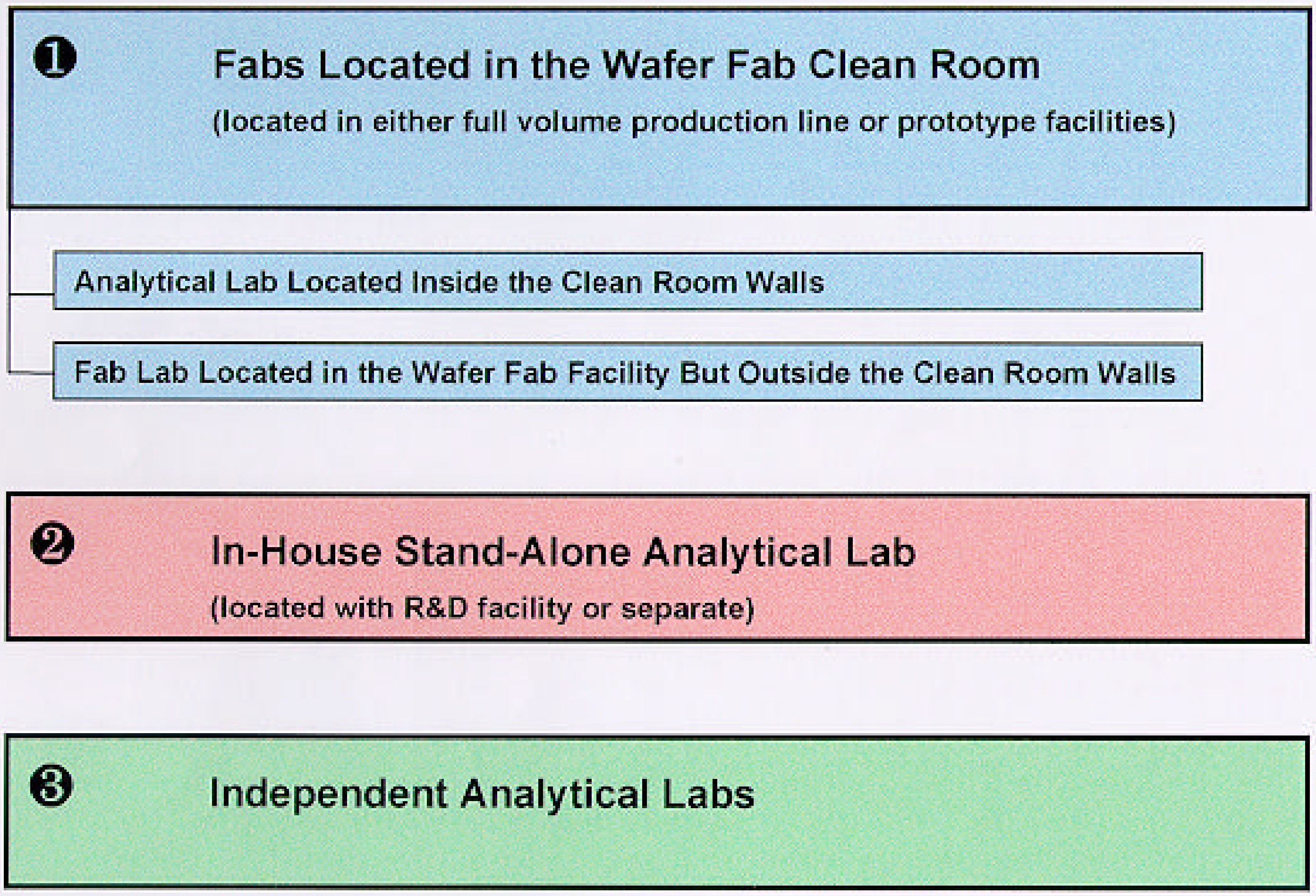
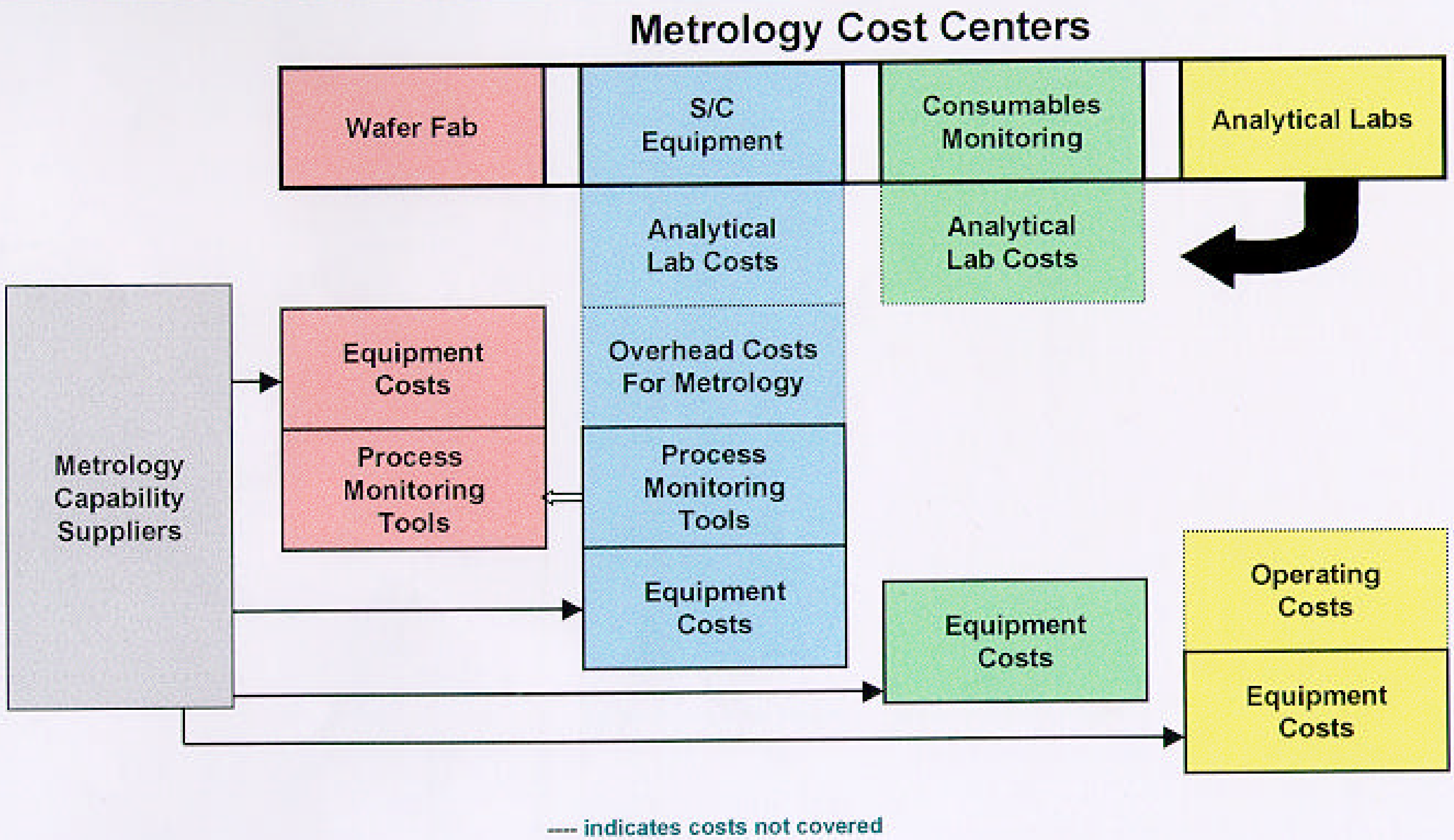


Figure 5

Metrology Capability Suppliers Supply the Metrology Cost Centers With Equipment/Instruments



Technecon Analytic Research

Appendix A
Measurement-Related Attributes

Appendix A

Measurement-Related Attributes

- **Temperature:** Absolute temperature and temperature gradients are important parameters in both machine condition and processing and processed material condition that need to be controlled. Also important is temperature rate of change. The concept of thermal budget refers to the integrated time-temperature a wafer has spent in order to control the redistribution of dopants in the device structures.

- **Physical Dimensions:** Physical dimension attributes cover device structure dimensions including layer thickness, line widths, positions of features, including overlay. Wafer position and orientation may fall in this category, with some overlap with the Handling attributes. Other physical dimensions that need to be considered and monitored could include machine state dimensions where wear is an issue -- thickness of sputtering targets as an example. Weights, where they are monitored, would be in this category.

- **Pressure:** Total and partial pressure of gases and perhaps liquids, partial pressures of gases in reduced atmosphere and vacuum environments, are important parameters that need to be monitored and controlled.

- “**Dose:**” This refers to the amount of dopants or radiation that are deposited on the material being processed. Radiometric measurements overlap somewhat with the next attributes category in my mind.

- **Optical Properties**: The intensity, polarization, spectral distribution, line width, band width, time dependence, coherence, are all possible parameters in this category.

- **Flow Rates:** This category includes not only gases and liquids used for processing the materials, but also where liquids or gases are used for heat transport, such as constant temperature wafer stages. Flow rates may be measured as mass flow rates or as volume flow rates.

- **Contamination:** Particulate sizes, positions, size distributions, and composition on wafers being processed, and in processing environments are monitored and controlled. Chemical contamination of processing gases and liquids, and chemical contamination of surfaces of processing chambers and wafer handling equipment and wafer carriers need to be monitored. Resistivity, pH, total oxidizable etc., are monitored in processing fluids such as de-ionized water and isopropyl alcohol.

- **RF Power:** Frequency, phase, power levels, both incident and reflected, come to mind for this category.

- **Handling:** This category refers to machine state; where are the wafers, conditions of valve settings, chamber doors, are relevant parameters. There is some overlap with the Physical Dimension attributes.

- **Effluents:** Liquid and gaseous emissions downstream from processing steps are monitored for environmental reasons and also perhaps for end point detection.

- **Time:** Processing time can be monitored to control other parameters. Time of day and date are used in data logging.

- **Magnetic Field**: Magnetic field strength and shape/orientation are important parameters, especially in plasma processing and ion implantation.

- **End-Point Detection:** End-point of processing steps is commonly monitored by a variety of means. These can be changes in the reacting gases or fluids, changes in the plasma, or direct observations of the processed material, usually optically.

- **Chemical Composition:** The compositions of reactants and formed materials on the processed material are commonly monitored. Liquid bath compositions are monitored to determine when the bath needs attention. I assume de-ionized water measurements are included under the Contamination attributes.

- **Stress and Strain:** This attribute is monitored in layers formed in and on the processed material, as well as in the packaging structures.

- **In-line Electrical Test (resistivity):** This attribute is measured in-line by process equipment.

Table A.1
Measurement-Related Capabilities by Category of Wafer Processing Equipment

Measurement Attribute	Resist Processing Equipment	Optical Exposure Systems	Direct Exposure Systems	Mask Exposure Systems	CMP	Ion Implanters	CVD	Diffusion Oxydation
1. temperature gradient & absolute	★	★	★	★	★	★	★	★
2. physical dimensions thickness / weight / position	★	★	★	★	★		★	★
3. pressure total / partial	★	★			★	★	★	★
4. “dose” radiometry flux	★	★	★	★	★	★		
5. optical properties intensity polarization spectral distribution / bandwith		★			★		★	★
6. flow rates	★ deposited volume				★	★	★	
7. contamination particulates (size / distribution) gas phase	★				★	★	★	★
8. Rf power						★	★	
9. handling	★	★	★		★	★	★	★
10. effluents	★				★	★	★	
11. time interval	★	★	★	★	★	★	★	★
12. magnetic field measurements				★		★		
13. end-point distribution emission / coherence shift composition					★	★	Not currently – but would like	★
14. chemical composition liquid & solid (excluding gases)	Off-line						Off-line	
15. stress & strain	Off-line						Off-line	
16. in-line electrical test resistivity	Off-line						Off-line	

Table A.1

Measurement-Related Capabilities by Category of Wafer Processing Equipment (continued)

Measurement Attribute	RTP	Dry Etch	Dry Strip	Wet Wafer Processing	Automated Handling Systems	Effluent Management Systems	Sputtering PVD	Electroplating
1. temperature gradient & absolute	☆	☆		☆			☆	☆
2. physical dimensions thickness / weight / position	☆	☆			☆		☆	☆
3. pressure total / partial	☆	☆	☆	☆			☆	Not yet important
4. “dose” radiometry flux	☆							
5. optical properties intensity polarization spectral distribution / bandwith	☆	☆						
6. flow rates	☆	☆	☆	☆		☆	☆	☆
7. contamination particulates (size / distribution) gas phase	☆	☆	☆	☆	☆	☆	☆	☆
8. Rf power		☆	☆				☆	
9. handling	☆	☆	☆	☆	☆		☆	☆
10. effluents	☆	☆	☆	☆		☆		☆
11. time interval	☆	☆	☆	☆	☆		☆	☆
12. magnetic field measurements		☆					☆	
13. end-point distribution emission / coherence shift composition		☆			☆		Trying to obtain capability	☆
14. chemical composition liquid & solid (excluding gases)				☆		☆	Off-line	
15. stress & strain	☆						Off-line	
16. in-line electrical test resistivity	☆							

Appendix B
List of Segments

Metrology-Related Segments Used to Define
Metrology Capabilities Suppliers

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These segments cover both metrology products and metrology applications.

1. Analysis / Measurement
   a. defect detection
   b. film thickness
   c. microscopes
   d. SEM
   e. SIMS
   f. surface inspection / flatness
   9. X-ray

2. Assembly / Hybrid
   a. inspection

3. Clean Room
   a. monitoring systems

4. Process Chemicals
   a. control handling
   b. monitoring equipment

5. Inspection Equipment

6. Process Equipment
   a. measurement equipment
   b. in-line inspection

7. Process Gases
   a. analysis standards
   b. control handling
   c. monitoring equipment

8. Services
   a. measurement / inspection

9. Test
   a. failure analysis
   b. temperature / environment / pressure

Appendix C
Individuals Interviewed

List of Interviewees

1. John Fehr, Motorola (abatement)
2. Pat Gabella, SEMI/SEMATECH
3. Mike McGraw, SEMI/SEMATECH
4. David Jensen, SEMATECH
5. Alain Diebold, SEMATECH (analytical labs)
6. Fred Streiter, formerly with Texas Instruments (clean room)
7. David Perloff, (Voyan Technology (measurement instruments)
8. Jeff Bindell, Lucent (analytical labs)
9. Fred Norton, AMD (bulk chemical & gas delivery)
10. Ana David, Union Carbide (bulk & specialty gas delivery)
11. Bob Bachrach, Applied Materials (process tools)
12. Henry Moore, Hewlett-Packard (clean room monitoring)
13. Mike Gordon, Texas Instruments (gases, di-ionized water)
14. Tom Shaffner, Texas Instruments (analytical labs)
15. Anonymous (chemical delivery systems; CMP slurry)
16. Ed Millis, consultant (clean room monitoring)
17. Anonymous (photolithography)
18. Ken Medearis, consultant (vibration measurement for structures)
19. Carl White, Motorola (vibration measurement)
20. Jose Frausto, Motorola (fluid flow monitoring)
21. Jim Intrater, Oryx Technologies (electro-static discharge measurement)

Appendix D
Example of Questionnaire Used in Interviews

Estimating Metrology-Related Costs
For Electroplating Equipment

This study is conducted under the sponsorship of
the National Institute of Standards and Technology ("NIST") for the purposes
of assisting in developing background information for application
in the Semiconductor Technology Roadmap

Objective

This study is being carried out under the sponsorship of the NIST. NIST is seeking to quantify the dollar amount of metrology-related investments made by the semiconductor industry in total and by major category for the years 1990, 1995 and 2000.

What We Need From You

You have been identified as an expert on a particular technical area we are seeking information on. We need you to provide us with your best estimate for % of metrology-related costs embedded in the total value semiconductor equipment system you are an expert on. Please note that we have structured the information collection process to ensure that we are not seeking to obtain company sensitive data.

This questionnaire seeks information related to metrology-related costs embedded in Electroplating equipment. We need you to estimate the % of total Electroplating system equipment value (i.e., cost to the end-customer) related to providing the metrology capabilities we define on the following page. These metrology capabilities relate to both monitoring and controlling tool functions as well as monitoring product quality. After reviewing the following list of measurement attributes of Electroplating TOOLS, ***please complete TABLE A and fax or mail it to:***

William F. Finan
Technecon Analytic Research
2445 M Street, N.W. Suite 200
Washington, D.C. 20037
Tel: 202-974-4663
Fax: 202-296-4008

Metrology attributes of Electroplating Equipment that we want you base you response in Table <A> on. That is, in providing your estimate for metrology-related costs embedded in an Electroplating system, we have identified that a typical Electroplating tool requires the following measurement capabilities:

Temperature: Absolute temperature and temperature gradients are important parameters in both machine condition and processing and processed material condition that need to be controlled. Also important is temperature rate of change. The concept of thermal budget refers to the integrated time-temperature a wafer has spent in order to control the redistribution of dopants in the device structures.

Physical Dimensions: Physical dimension attributes cover device structure dimensions including layer thicknesses, line widths, film thickness, positions of features, including overlay. Wafer position and orientation may fall into this category, with some overlap with the Handling attributes. Other physical dimensions that need to be considered and monitored could include machine state dimensions where wear is an issue -- thickness of sputtering targets as an example. Weights, where they are monitored, would be in this category.

Pressure: Total and partial pressure of gases and perhaps liquids, partial pressures of gases in reduced atmosphere and vacuum environments, that need to be monitored and controlled. NOT YET IMPORTANT.

Contamination: Particulate sizes, positions, size distributions, and composition on wafers being processed, and in processing environments are monitored and controlled. Chemical contamination of processing gases and liquids, and chemical contamination of surfaces of processing chambers and wafer handling equipment and wafer carriers need to be monitored. Resistivity, pH, total oxidizables etc., are monitored in processing fluids such as de-ionized water and isopropyl alcohol,

Contamination: Particulate sizes, positions, size distributions, and composition on wafers being processed, and in processing environments are monitored and controlled. Chemical contamination of processing gases and liquids, and chemical contamination of surfaces of processing chambers and wafer handling equipment and wafer carriers need to be monitored. Resistivity, pH, total oxidizables etc., are monitored in processing fluids such as de-ionized water and isopropyl alcohol.

Time: Processing time can be monitored to control other parameters. [Note: some reviewers believe this category is no longer applicable since events are monitored, not time per se.]

End-Point Detection: End-point of processing steps is commonly monitored by a variety of means. These can be changes in the reacting gases or fluids, changes in the plasma, or direct observations of the processed material, usually optically. In this case it is the total change in thickness being measured.

TABLE <A>
Electroplating Equipment
Please complete this table providing the % of total system cost related to providing the measurement capabilities listed above for Electroplating Equipment.

(Note: "System cost" is defined as the total value of the system as purchased by an end customer, that is, estimate measurement costs as a % of the total end-value of the system to the customer.)

Enter your estimate of embedded measurement costs as a % of total "system cost" for the period specified	LOW estimate for measurement costs as % of total system cost	HIGH estimate for measurement costs as % of total system cost
Year 1990 0.8μ - 1.0μ front end		
Year 1995 0.5μ front-end		
Year 2000 0.35μ or below		

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Appendix E
List of Metrology Capability Supplier Companies

Available in hard copy only.