

Benchmarking Semiconductor Manufacturing

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Abstract

We are studying the manufacturing performance of semiconductor wafer fabrication plants in the US, Asia, and Europe. There are great similarities in production equipment, manufacturing processes, and products produced at semiconductor fabs around the world. However, detailed comparisons over multi-year intervals show that important quantitative indicators of productivity, including defect density (yield), major equipment production rates, wafer throughput time, and effective new process introduction to manufacturing, vary by factors of 3 to as much as 5 across an international sample of 28 fabs.

We conduct on-site observations, and interviews with manufacturing personnel at all levels from operator to general manager, to better understand reasons for the observed wide variations in performance. We have identified important factors in the areas of information systems, organizational practices, process and technology improvements, and production control that correlate strongly with high productivity. Optimum manufacturing strategy is different for commodity products, high-value proprietary products, and foundry business.

Introduction

This comparative study involved the measurement of manufacturing performance and investigation of underlying determinants of performance at 28 wafer fabrication facilities in the United States, the United Kingdom, Germany, Spain, Japan, Korea and Taiwan. The companies operating these facilities are displayed in Table 1.

Companies Participating in the Main Phase of the Competitive Semiconductor Manufacturing Survey	
Advanced Micro Devices, Inc. (AMD)	National Semiconductor Corp. (2 fabs)
Cypress Semiconductor, Inc.	NEC Corp.
Delco Electronics Corp.	Oki Electric Industry, Ltd.
Digital Equipment Corp. (2 fabs)	Samsung Electronics Co., Ltd.
Harris Corporation	Silicon Systems, Inc. (SSI)
Hyundai Electronics Industries, Ltd.	Sony Microelectronics Corp. (2 fabs)
Intel Corporation	Taiwan Semiconductor Mfg. Corp. (TSMC)
Int'l Business Machines, Inc. (IBM)	Texas Instruments, Inc.
ITT Intermetall	Tohoku Semiconductor Corp. (TSC)
LSI Logic Corp. (2 fabs)	Toshiba Corp.
Lucent Technologies (2 fabs)	United Microelectronics Corp. (UMC)
Motorola, Inc.	

Table 1

Each participant completes a 100-page questionnaire covering objective data including clean room size and class, head counts, equipment counts, wafer starts, die yields, line yields, cycle times, computer systems, etc. over the preceding four years. From this data we calculate technical metrics of manufacturing performance for each participant. We then compare performances on each of the metrics.

We observe great variations in the scores of the various participants. To understand what practices account for such performance differences, we conduct a two-day site visit with each participant. We tour the manufacturing line, interview a cross-section of the entire fab staff, and hold discussions concerning strategies for improving yields, increasing wafer throughput, reducing cycle times, etc. We survey each firm's activities to improve computer integrated manufacturing (CIM) and information systems, human resources development, effectiveness of work groups and teams, etc. These more qualitative indicators of participants' operational practices are then correlated with the performance scores to identify those practices that underlie good or bad performance. Performance and practice comparisons are separated into VLSI memory, VLSI logic, and MSI categories, according to the type and sophistication of devices that are fabricated. The individual identities of the participating fabs are coded. Each participant receives all the comparative data but knows only its own code identifier.

Metrics of manufacturing performance

We use the following technical metrics to measure manufacturing performance:

- Average line yield, the percentage of wafers started that are completed properly, normalized to twenty mask layers.
- Defect densities, calculated for major process flows in each fab by using reported die yields and die sizes in the Murphy model of defect density. The reported defect densities account for all yield losses, including both spot defects and parametric problems. For memory products, the die yields applied to the defect density formula are final die yields after laser repair.
- Integrated fab and die sort yield, calculated as the product of line yield per twenty masking layers and the estimated die yield for a 0.5 sq cm die. This die yield is estimated using the Murphy defect density calculated from reported die yields as described above.
- Wafer masking layers completed per 5X stepper per calendar day (considering only layers exposed using 5X steppers).
- Wafer implant layers completed per ion implanter per calendar day.
- Wafer metal layers completed per metallization machine per calendar day.
- Integrated 5X stepper throughput, the equivalent number of full-wafer operations per 5X stepper per day, calculated as the number of 5X wafer operations per day times the integrated yield defined above.
- Average cycle time per mask layer.
- Wafer masking layers completed per operator per working day (considering all masking layers, regardless of type of lithography equipment).
- Wafer masking layers completed per working day divided by the total head count.

For all of these metrics, we encountered a wide range in scores, even though the basic process technology in use at the participants was generally similar. Table 2 summarizes scores for each

metric for the CMOS memory category, considering the latest data points we received from each of the 28 participants. Similar spreads in the data were found also for CMOS logic fabs. The time interval covered is from the middle of 1992 to the middle of 1995.

Rates of improvement were studied for each participant. Scores for each technical metric were computed for each quarter over a period of three to four years. For most metrics, the ranking of participants changes slowly, i.e., we found few cases where a last-place participant overtook the leader for a particular metric, although some participants improved their rankings considerably over the period.

One of the most striking trends we observed in our measurements concerns the initial defect densities for process flows, i.e., the defect densities realized in the first calendar quarter after transfer of the process flow into manufacturing. We recorded a factor-of-ten range in initial defect densities. Those fabs with poor starting points tend to have faster rates of improvement, but not nearly fast enough to overtake those with good starting points, at least not for several years, as those with good starting points also make steady if somewhat slower progress reducing defect densities.

The integrated stepper throughput metric is perhaps our best indicator of overall fab productivity, at least for submicron fabs dependent on this technology for photolithography.

The varying strengths and weaknesses in line yield, die yield (defect density) and stepper throughput among our participants are integrated to see the overall throughput of good silicon per machine. Even for such an integrated metric, we find a remarkable factor-of-seven range in performance.

Technical Metric Scores: Memory Fabs			
Metric	Best	Avg	Wrst
Line yield per twenty layers (%)	98.8	93	87.1
Murphy defect density - 0.45 - 0.6 micron CMOS memory (defects per sq cm after repair)	0.03	0.59	1.34
Murphy defect density - 0.7 - 0.9 micron CMOS memory (defects per sq cm after repair)	0.01	0.51	1.81
Murphy defect density - 1.0 - 1.25 micron CMOS memory (defects per sq cm after repair)	0.31	0.59	1.08
Integrated fab and sort yield (%) 0.45 - 0.6 micron CMOS memory (0.5 sq cm device)	91.7	72.1	46
Integrated fab and sort yield (%) 0.7 - 0.9 micron CMOS memory (0.5 sq cm device)	92.9	73.9	35.9
Integrated fab and sort yield (%) 1.0 - 1.25 micron CMOS memory (0.5 sq cm device)	77	66.7	48.3
5X Stepper throughput (wafer operations per 5X stepper per day)	606	463	281
Ion implanter throughput (wafer operations per implanter per day)	1360	855	339
Metallization throughput (wafer operations per machine per day)	273	147	53
Integrated 5X stepper throughput (Full-wafer ops/stepper-day)	479	344	160
Cycle time per mask layer (days)	1.8	2.9	4.1
Direct labor productivity (mask layers completed/operator-day)	71.7	42.6	18.4
Total labor prod. (mask layers/p-d)	51.6	27.3	15.1

Table 2

Practices underlying manufacturing performance

Our main objective is to identify those operational practices that underlie leading-edge manufacturing performance. Summarized below are the operational practices that distinguish those fabs achieving best or near-best scores in one or several of the metrics described above. (For the sake of brevity, we refer to such fabs as the “leading” fabs.) But before summarizing our findings in that regard, it is only fair to acknowledge that our analysis does not account for several strategic factors concerning product design and fab design that may strongly influence manufacturing performance.

First, the restrictiveness of product design rules can have a strong influence on observed die yields and hence on our calculated defect densities. We made no attempt to normalize defect density scores for potential differences in design rules among the participants.

Second, the range of sizes of fabs in our survey, in terms of wafer starts, spans a factor of almost fifty. Small fabs generally have inferior labor and equipment productivity scores, because of the indivisibility of machines and personnel, and because of the tendency to install extra equipment to avoid situations in which a particular process step must be performed by a one-of-a-kind equipment type. In the tables of metric scores, we do not adjust productivity scores to account for fab size. For a general assessment, we define as large fabs those that make more than 7,000 wafer starts per week, medium fabs that make 2,500 - 7,000 wafer starts per week, and small fabs at less than 2,500 wafer starts per week. Large fabs lead almost every one of our labor and equipment productivity metrics, although fab size above 7,000 wafer starts per week does not improve performance. In the yield and defect density metrics, small and medium fabs are competitive with the large fabs.

Third, using older-generation processing equipment on newer process flows may make the achievement of world-class defect densities much more difficult than if newer equipment is used. While yields may be lower when employing older processing equipment, capital costs are lower as well, and so the strategy might turn out to be economically competitive or even superior to the strategy that employs solely new processing equipment. We made no attempt to adjust defect density scores for the generations of equipment applied.

With these strategic factors aside, we now summarize the various operational practices we found to be correlated with good manufacturing performance (in terms of the manufacturing metrics we have defined). We define eight basic themes for key practices that underlie leading performance. In short, these themes are:

1. Make manufacturing mistake-proof
2. Integrate process, equipment and product data, and analyze it statistically
3. Automate information handling and step-level material handling
4. Develop a problem-solving organization
5. Reduce the division of labor
6. Secure the requisite technical talent
7. Manage new process introductions
8. Schedule manufacturing activity

Proper execution of the very complex manufacturing process is essential. Some participants with a narrow product mix and very disciplined, well-trained operators achieve high line yields with little or no automation. But other leading participants have applied very effective forms of information automation that make manufacturing very mistake-proof. Such automation includes procedural checks that require the right production lot and the right machine to be selected before processing activity may be initiated, and automated download of the machine recipe (i.e., the processing parameters) to the processing machines.

Good process control systems do not make manufacturing strictly mistake-proof, but they serve to contain losses to minimal levels. All fabs in our survey apply SPC to their processes and equipment. The leading fabs make considerable use of sensors and computers to monitor equipment performance, and provide automated notification of out-of-control conditions and on-line assistance for trouble-shooting.

The leading fabs utilize computerized tracking systems to achieve excellent data collection and excellent data analysis capabilities. They collect large amounts of data concerning process and product conditions (an activity termed engineering data collection, or “EDC”), equipment maintenance and operation history, lot production history, and yield results. They integrate these data in a single relational database. Statistical tools are routinely applied to these data by process engineers, enabling them to expeditiously pinpoint causes of low die yields and make rapid deployment of counter-measures to contain losses.

The leading fabs rigorously measure the overall equipment efficiency (OEE) of their key processing equipment, identifying losses in throughput and prioritizing needed improvements. In the best fabs, equipment status is automatically captured from machine logs using SECS-II interfaces. Actual processing time is automatically monitored and compared against engineering standards; alarms are triggered when elapsed times are excessive.

Automation of information handling and step-level material reduces the overhead surrounding the performance of processing steps. Automation of information handling includes procedural checks and auto-recipe download as described above. It also includes automated capture of engineering data and equipment tracking data using bar codes and sensors, as well as automated notification of operators or technicians when machines are about to become idle or when they require maintenance or attention.

Material handling automation efforts may be divided into three types: interbay automation, intrabay automation, and step-level automation. Interbay automation concerns the movement of production lots between equipment bays using automated guided vehicles (AGVs) or overhead tracks to transport lots between stockers serving the bays. Intrabay automation concerns the movement of lots between stockers and processing machines in the bay using AGVs or traveling robot arms. Step-level automation involves the use of robot arms or tracks to handle wafers or cassettes of wafers between lot box and processing chamber, or between consecutive processing chambers. We find that step-level automation has the greatest positive impact on fab performance among our participants. For instance, fabs that have linked up coat, expose and develop steps in photolithography into a single automated sequence achieve higher yields and lower cycle times with no reduction of equipment throughput.

Fabs that have developed a strong problem-solving organization are very good at problem recognition, problem solving, and elimination of repetitive problems. Semiconductor manufacturing is characterized by immature processes and immature equipment, and by continuing increases in complexity. Opportunities to improve yields and/or wafer throughput are

always present. Thus manufacturing has a major engineering aspect as well as the expected operational character. This means a fab must continually develop technical competence of its organization and continually foster a teamwork approach to recognize problems, devise innovative solutions, and implement them quickly and successfully. The leading fabs have instilled problem-solving skills in their technicians and operators through extensive training, mentorship and participation in continuous-improvement teams organized under the TQM and TPM paradigms. TQM (Total Quality Management) focuses on product quality, while TPM (Total Productive Maintenance) focuses on equipment productivity.

Leading fabs have strong internal technical talent complementing support from vendors to expeditiously modify product, process, and equipment to implement changes that have been identified by problem solving efforts as desirable or necessary. In particular, leading fabs have considerable in-house equipment engineering talent, identifying and implementing useful modifications to process equipment that improve performance or ease maintenance. In contrast, weak-performing fabs have process engineering organizations that are virtually devoid of equipment engineering skills.

Reducing division of labor involves training efforts and job expansions to reduce response time to problems and to promote more effective formulation of engineering solutions. Operators at leading fabs are trained to perform basic equipment maintenance and trouble-shooting, enabling them to be pro-active instead of waiting for a technician when the need for maintenance or correction arises. In such fabs, each equipment bay on every operating shift is staffed with a technician or operator designated as the “key man” for that type of processing equipment. This person trains and focuses the rest of the staff for improved equipment operation and maintenance, responds immediately to problems that may arise, and serves as a technical resource and mentor for other operators.

Technicians and operators work together in leading fabs on continuous improvement teams, directed and supported by engineers. Such teams identify and research process and equipment problems, find root causes, and then devise, test and implement permanent fixes. The teams serve to expand the knowledge, skills, confidence and job scope of all personnel.

The division-of-labor theme also applies to engineers. Process and equipment engineering groups are merged in leading fabs, broadening the skills of engineers and promoting quicker identification and implementation of effective solutions to process and equipment problems. Rather than being exclusively the domain of statisticians or of yield and integration engineers, statistical analysis of yield is practiced regularly by process engineers at leading fabs.

Leading fabs have effective procedures for managing the introduction of new process flows. The economic life of many process flows is three to four years, with unit prices for products of the flow declining rapidly over this period. Thus it is economically important to realize high productivity quickly after process introduction, and to fairly frequently introduce new process flows. A poor start with a new flow may leave the fab too far behind to catch up before the market value of the output has declined.

The leading participants strategically stagger transitions to new product generations and new process generations, and control the number of new modules in each process generation to keep the difficulties at each step to a tractable level.

The leading participants also have effective operational procedures for new process transfer. Identical equipment sets are used in development and in production; development and volume

production are often co-located. Transfer of process documentation is electronic. Engineers from the recipient manufacturing fab participate in the final stages of development.

Rigorous scheduling of production activity aims at reducing cycle time and improving on-time delivery. The leading fabs utilize automated production planning systems that insure releases of new production lots do not overload fab resources and that target out schedules are consistent with steady flow of work-in-process (WIP) according to target cycle times. Delivery quotations to customers are automatically made on the basis of the planned production. Dispatching of lots on the factory floor is performed to prioritize lots that are behind schedule, supplemented with Kanban controls that ensure WIP is kept in balance.

Practice trends

Each participant tended to score well or score poorly in most metrics, reflecting the fact that particular practices, good or bad, tend to influence several metrics. Yet almost every participant pursued at least one good practice that we did not find elsewhere, whose adoption by the other participants we believe would improve performance.

No single fab is the leader in all eight themes described above. The best integrated database and best statistical yield analysis system we saw was in a Korean fab; the best equipment efficiency analysis system was in a Japanese fab; the best information handling and step-level automation implementation we saw was in a fab in Taiwan; and the best cycle time control and on-time delivery systems we saw were in fabs in the United States.

In cases where a fab scored poorly for certain metrics, the most common reason was that the relevant area was simply not a focus of the fab management. Every participant has certain focus areas that management impresses on the work force as top priorities for improvement; associated with each area is a paradigm for data collection, problem-solving, training, etc., that we call a culture. We use the term culture because of the management efforts clearly made to rally the organization around a unifying theme aimed at improved performance.

Manufacturing cultures we encountered include TQM with its focus on product quality and process control, TPM with its focus on equipment productivity, intensive in-line data collection and statistical analysis of the integrated data, automation for mistake-proofing and productivity improvement, fast cycle time (“time-based competition”), and on-time delivery. These cultures are not really exclusive, but many times we observed how a fab, stuck in the paradigms of its culture, simply had not placed any focus on certain areas of improvement.

We observed varying strengths of different cultures in different parts of the world. TQM was well-established almost everywhere. Intensive in-line data collection and statistical analysis of integrated data is strong in at least two thirds of our participants, representing all parts of the globe. TPM is very strong in Japan and in some companies in Taiwan and Korea, but generally weak in the US fabs we visited. On the other hand, cycle time and on-time delivery are strong cultures in US and Taiwanese fabs, but generally quite weak in Japanese and Korean fabs. No doubt our participants are working to catch up in their areas of weakness.

Since the TPM culture originated in the Japanese machine tool industry, the fact that it has become strong in the Japanese semiconductor industry is perhaps not surprising. What is more surprising is that the cycle time culture, which first flowered in the Japanese automobile industry, flourishes in many American semiconductor fabs we saw, has not taken hold yet in most Japanese semiconductor fabs we visited.

With the maturity of TQM and the integrated data analysis cultures at most of our participants, defect densities are quite competitive at many of our participants, apart from performance differences associated with weaknesses in process development and transfer. Given the weaker penetration of the TPM culture and of the information handling and step-level automation culture, equipment throughputs and line yields are more prominent discriminators of fab performance in our sample. Unique specific process technologies are a relatively insignificant factor differentiating manufacturing performances.

The limited penetration of cycle time and on-time delivery cultures also ought to discriminate performance in semiconductor manufacturing. However, the importance of good performance on these measures varies depending on product category. They are relatively unimportant for commodity memory products, but at the other extreme, critically important to foundries that serve fabless semiconductor firms.

Plans for further work

Currently we are extending the benchmarking study to include the 200 mm. generation of fabs. Separately, we are studying in much greater detail the factors contributing to overall equipment efficiency (OEE). Now that line yield and die yield have reached very high levels, equipment efficiency has become the area offering best opportunities for increased productivity. On another track, we are studying the factors that contribute to the excellent success of the “fabless-foundry” business model. This business model produces short time-to-market for new products with relatively low business risks to all parties.

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Acknowledgements

We acknowledge the valuable contributions of many students and of Professors D. C. Mowery (Haas School of Business), C. Brown (Institute of Industrial Relations), M. Borrus (Berkeley Roundtable on the International Economy) and C. N. Berglund (Oregon Graduate Institute). The Alfred P. Sloan Foundation of New York has provided grant support since 1991. SEMATECH, the Semiconductor Research Institute of Japan, the Electronic Industry Association of Japan, and several of the participating companies have given important additional financial support.

Q & A from the Integrated Reliability Workshop, 10/13/97

Q: What correlation do you observe between wafer throughput and yield?

A: We saw one extreme case of an excessive focus on yield, via heavy use of inline monitoring and rework, that reduced wafer throughput and total output. Raising yield from 85% to 92% is not worth a 20% reduction in wafers processed! In general, however, better performers were more balanced, and were focussed on total output.

Q: What correlation do you observe between effectiveness of SPC activity and cycle time?

A: We have not studied that specific point, though we could do it with our data set.

Q: How widespread is the use of automatic recipe download to processing equipment?

A: Far from universal. Fabs running only one process, or with only minor variations, don't need it. However, the best fabs employing a considerable range of process parameters have implemented auto download to minimize misprocessing.

Q: To what extent do you see use of multivariate statistical analysis in manufacturing?

A: Not much in manufacturing. However, principal components analysis and multivariate analysis are heavily utilized in process development prior to transfer to manufacturing.

Q: How are process and product changes staggered in logic and ASIC fabs?

A: Foundries generally offer several mature fab processes. They encourage inexperienced customers to work with these. New process generations may be introduced in a partnership with selected highly experienced customers who are willing to endure the risks and costs of advanced technology.

Q: What patterns do you observe in process change control?

A: There must be a formal, documented procedure for evaluating potential process changes and for making a decision and assigning responsibility for introducing any process change.

Q: How can a firm be ahead in planning and scheduling, yet behind in equipment throughput?

A: Firms in this category are well-disciplined in utilizing a defined machine capacity. But the total output they achieve is significantly below the best.

Q: Do you normalize for number of mask layers in your figures on integrated chip yield?

A: Line yield is normalized to 20 layers. Probe yield is not adjusted for layer count, but includes memory chips that are repaired with redundancy. Integrated yield is the product of these two.

Q: Have you seen single fabs that are excellent simultaneously in logic and memory?

A: This is unusual, but at least one of the top performers achieves good results with a very large mix of memory and logic products in continuous production. They have invested heavily in automatic reticle changers and autorecipe download. This is a very disciplined organization.

Q: To what extent do you see non-product production wafers devoted to process control, quality control, etc?

A: Everyone is trying to minimize fabrication of non-product wafers. Test structures are placed in scribe lines of every production wafer. Introduction of new process modules may involve short-loop processing of test wafers. We did not collect data on this activity.

Q: As semiconductor manufacturers make transitions from 6" to 8" and then to 12", are good practices carried over? And where are all the skilled technical and professional people coming from to staff all the new fabs under construction?

A: In general, internally companies move experienced people from older fabs into new ones. In most cases where we have benchmarked 2 fabs of one company, similar practices are evident in both fabs. Concerning staffing of new fabs, one company that is building new fabs seemed overstaffed with engineers in the fab we benchmarked; but perhaps this is in preparation for anticipated needs.

Q: Have you compared the time required for a cycle of learning (production cycle time plus time for analysis and decision-making) at different companies?

A: No. This would become more important if we observed bigger differences in rates of improvement at different fabs.

Q: Have you studied any fully automated fabs?

A: None. One company that built and operated such a fab in the past said they would not do it again, because it was too inflexible for making changes and improvements.

Q: Your production cycle time seem to be those for normal production lots? How much faster are "hot lots"?

A: We did not collect any such data, but we know that "hot lots" can be considerably faster.

Q: Why are the rates of improvement in yield (and other measures) so similar among fabs?

A: This is an interesting question. We expected to find bigger differences. Empirically, most manufacturing industries observe similar uniformities in improvement rates. Much research has been conducted on possible underlying fundamentals (key words: "learning curve" and "progress function"), without much satisfaction.