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Guest Article
特集寄稿

The Trends in Semiconductor Process Control in the Next Generation Devices

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In 1965, Intel co-founder, Dr. Gordon Moore made the prediction that the number of transistors on processors would double every two years, and the semiconductor industry has marched to the beat of his prediction ever since. Since 1970, semiconductor technology advances have led to 30% annual declines in the price of microprocessor performance (measured in one million instructions per second (MIPS)). No other industry has achieved such technological success. Over the last 10 years alone, the semiconductor industry has grown at rate of 15.7%, almost three time that of the the U.S. economy. Capital spending for the last 10 years is eight times greater for the semiconductor industry than other high technology areas.

The 1997 revision of the National Technology Roadmap for Semiconductors has shown that semiconductor device development had accelerated from the previous roadmap, which was issued in 1994, from a three year development cycle to a two year development cycle. This acceleration affects the development of equipment, materials, process control, and all support infrastructure for device manufacture, too. These facts constantly challenge the participants in the semiconductor industry to manufacture more effectively, utilize the equipment and materials more efficiently, make decisions quicker and ramp yields faster. A large component for success in the future will rely on improved, fast cycles of learning which are dependent on data acquired on wafers, process, equipment and manufacturing indices which has been summarized, decisions made upon and implemented with minimal to no human intervention. Process control provides solutions in the form of automated data collection, summary/filtering of data to make it more useable (data-to-information), attaching knowledge information to the data point or set, modeling and algorithms applied to make decisions on the data and then those data sets and decisions can be taken to the next level which is to provide feedback to the system (on which the data is collected) and improve the system (process, equipment, manufacturing indices). Improvement can come in the forms of improved tool cost of ownership (CoO, Table 1), better overall equipment efficiency, more repeatable process and repeatable device performance, and better factory performance (cost, output, cycle time, quality). Though this article is focused on wafer processing, some of the same methodologies can be applied to factory automation, facilities and manufacturing indices.

"If it was possible for the auto industry to achieve similar technological progress to the semiconductor industry, the FORD Taurus that first sold in 1986 for $10, 000, would cost about $150 today." (SIA, 1998)

次世代半導体デバイスの製造プロセス制御の新たな動き

1965年にインテルのDr. Gordon MooreはCPU用トランジスタは２年毎に倍増すると予測した。以来，半導体技術・業界の躍進は目覚しく，最近10年間の成長率は15.7%にもなっている。

半導体デバイスの開発サイクルはますます加速されており，National Technology Roadmap for Semiconductors (1997年度版)によると，1994年当時は３年であったが，現在では２年へと短縮されている。このため，材料，プロセス制御，デバイスメーカーなど半導体に関連する全ての業界で，生産効率の上昇，装置や材料の利用効率の向上，意思決定の迅速化，利潤回収の短期化に絶えず迫られている。

「自動車業界が半導体業界なみの技術的進歩を達成できていたなら，1986年の新発売時に販売価格が＄10, 000であったフォードのタウラスは，現在では＄150前後となっていたはずだ」(米国半導体工業会(SIA)，1998より)

1. Why is Process Control and Diagnostics Important for the Future?

The semiconductor business is transforming from a commodity supplier model to a service model. The device manufacturers are being driven to get to market faster, serve smaller markets with application-specific designs, shorten the time to high yields and speed the rate of learning. Reduction of cycle time increases the manufacturing complexity. As you drive down cycle time and improve quality the unit volumes increase, and thus, the data volume and variance increase. Demands on new equipment, new materials and new processes requires more sophisticated and fast characterization methods. Engineering and manufacturing science requires data. Measurement methods collect data, data allows you to make decisions and solve problems. Data and the analysis of data helps "visualize" the system capability and system problems. You cannot understand (and fix) what you cannot measure. Problem solving, and gathering new insights requires a constant search for the appropriate measurement technology. Cost effective manufacturing requires that metrology to be used in a judicious fashion. As learning occurs, and equipment and processes become well characterized, the need for frequent and multiple metrology decreases. This new knowledge and new metrology technology can now be applied to the next generation of device manufacturing. When a method helps the factory to be more efficient, it will become second nature that that method will always be part of the manufacturing systems. Twenty years ago, statistical process control methods were rarely practiced in the semiconductor industry. Today, you would not run a factory without it. Ten years from now, similar statements will be made regarding process control methods.

2. What are the challenges facing the semiconductor industry in the near future?

- post-optical lithography
  - timing to change to post-optical
  - how far does optical go
  - cost of development of post-optical lithography systems
  - cost of development for the lithography infrastructure
    - resist, tracks, mask/reticles, metrology
- new materials / processing methods
  - copper for interconnect
  - low-k dielectrics for interconnect
  - high-k dielectrics for gate
- incremental changes
  - next wafer size: 300mm
  - increasing scale of integration
    - more transistors in same amount of space
    - more functionality on one chip
- improved manufacturing
- improved equipment productivity

3. How process control and diagnostics can help?

At today's high wafer values, the factory needs to be proactive not reactive, and on-line and in situ metrology and process control assist with being proactive because data-to-information occurs quickly, decisions occur quickly and it accelerates the learning curve. For example, factories with in-line inspection exhibit a 5% yield advantage over factories that do not utilize in-line inspection.
Table 1 list some benefits to equipment cost of ownership that can be realized with process control. Table 2 shows some of the additional benefits that can be had from both the device manufacturing perspective and the equipment supplier perspective.

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1. プロセス制御および診断が今後重要となる理由は

半導体事業は商品供給型からサービス型へと変貌しつつある。デバイス・メーカは，開発から発売，さらに高収益達成までの期間の短縮を迫られている。サイクルタイムの短縮，品質向上のためにはさらに高度かつ高速なプロセス管理が必要となる。科学的なエンジニアリングのためにはデータの収集・解析が基本となる。新たな視点をえ，問題解決を図り，製造コスト低減のためには，正しく賢い測定技術を絶えず追求しなければならない。

「統計的プロセス制御法の導入は20年前では稀だったが，今やこの手法を抜きに半導体工場は成り立たない。」と言われる。10年後も同じことが言われているであろう。

2. 近未来において半導体業界の抱える問題は何か

＊光学リソグラフィーの後継技術
＊新素材／加工方法
＊量の拡大
＊生産性の向上
＊生産設備の効率改善

Table 1 Improved cost of ownership (CoO) indices

- increased throughput
- decreased cycle time
- increased reliability
- decreased maintenance
- decreased consumables
- decreased footprint
- decreased scrap
- increased yield
- decreased monitor wafer usage
- decreased disposal
- decreased utilities
- decreased particles

Table 2 Benefits that Integrated Metrology Can Produce

■ For Integrated Circuit Maker; Process Itself:

- Increase productivity
  - -People
  - -Equipment
  - -Fab / cost effective manufacturing
  - -Technology transfer & ramp-up
  - -Sales (customer relations)
  - -Less redundant processing (metrology, cleans, inspections)
- Process stability
  - -Eliminate outliers
    - -Points not belonging to typical distribution
- Improve typical distribution (process stability)
  - -Drive average to target
  - -Reduce variance

■ For Equipment Supplier:

- Reduced engineering support
  - -Increases effective skill set of field service personnel
  - -Automatic re-tunings of process
  - -Diagnosis/prognosis to reduce down-time
  - -Quicker time to recover (repair & condition & tune & qualify)
- Intelligent maintenance
  - -Maintenance on need basis, scheduled when convenient (predictable preventive maintenance)
  - -improved spare parts management

4. Now and future metrology and process control scenarios

One method of classifying/describing the measurement tool is by physical location in the factory and how the metrology equipment is used in manufacturing. (Table 3).
These descriptions help in communicating various levels and capabilities of tool use.

Table 3 Measurement Tool Description

■ Stand-Alone Measurement Tool

Off-Line: outside of the fab, usually destructive or contaminating

At-Line: in the fab, monitor wafers since unable to measure pattern wafers; could also be destructive, or contaminating

In-Line: is or can be part of process flow routing, can measure pattern wafers

■ Integrated with the Process Equipment

On-Line: measurement tool integrated with process equipment, but not able to measure during wafer processing

In Situ: measures during processing

4.1 Today's metrology and control scenario

At-line or in-line metrology tool takes measurements on the wafer(s) from the last process, that data is charted, statistical process control methodology used to determined “goodness” of process and often “goodness” of equipment, material committed, repeat measurement on a frequency rate as determined by risk of not catching “bad” manufacturing. The measurement is perform on product (in-line; as processed wafers, patterned wafers) or on monitor wafers (at-line, unpatterned). Product is saleable, monitors are not. Yet some measurement techniques cause some damage to the wafers, have a high risk of contaminating the wafers or the measurement resolution is compromised due to the pattern, in those cases, monitors wafer are used. Some data analysis performed, mostly one parameter analyses with the start at multi-parameter

3. プロセス制御と診断の効用

今日のようにウエハの価格が高いと，事態が発生してからではなく事前に対応する必要がある。オンライン測定，現場測定とプロセス制御が事前対応に役立つ理由は，計測データを素早く解析し，迅速な決定ができる点にある。インライン検査を行っている工場では，実施していない場合に比べ，歩留まりが5%向上している。**表１**にプロセス制御の設備所有コスト面の利点(CoO)を，**表２**にデバイスメーカおよび製造設備機器メーカのメリットを示す。

4. 現在および将来の測定法とプロセス制御の考え方

計測機器は，どこで，どのような目的で使われるかによって分類**（表３）**される。

4.1 現状

アト・ラインまたはイン・ライン測定では，最終プロセスからウエハを測定し，統計的な工程管理手法により工程，設備，材料の「適合度」を判定するが，この方式では不良を見逃す危険もある。測定によりウエハに汚染や損傷が生じる恐れがあったり，測定方法が確立していない場合にはモニタ用ウエハを使っている。

analysis and also a start at some methodology applied to the data sets.

4.2 Transitioning to metrology and control scenario

Measurement data is automatically collected and some filtering/analysis is performed to determine “goodness” and turn data-to-information, perform fault detection (“go” or “no go” decision), and occasionally data analysis performed that produces input information/parameters which is fed back into the equipment and process to adjust their function which tightens the overall distribution on the material being processed (either “sneaker” method or automatically). (“Sneaker” method - a human takes the new calculated input parameters back to the process tool and readjusts the operating parameters by hand.) Data is collected via at-line, in-line, and occasionally on-line and in-situ. A lot of data analysis performed, still mostly one parameter analyses with the start at multi-parameter analysis. Expert methodology is getting broader application across the equipment and the process.

4.3 Future vision for the metrology and control scenario

Automated measurement and data collection, with heavy utilization of on-line and in situ metrology systems. Wafer state, equipment state and process state measurement capable by the metrology systems. This data is available to the factory data management and analysis systems. Often the data is filtered and labeled to provide information for independent decisions to be made. It certain cases control algorithm output parameters will be applied back to the process and equipment to improve the overall process capability, real time. Equipment will notify the factory when it needs preventive maintenance, or when it discovers out of control processing, and will help to qualify itself (shorten the qualification cycle). Expert methodology and data mining will be employed to preserve the knowledge base (source problems, found solutions) and locate data patterns to source problems more quickly. Multi-parameter analysis and methods utilized to expand characterization knowledge of the process and equipment. This knowledge enhances the factory’s ability to control the equipment and process and tighten the overall distribution, thus producing more predictable and reliable product.

(note: various parts of the “now, transition and future” scenarios may exist in one factory today as the semiconductor manufacturer strives for improvements.)

Table 4 list some of the future opportunities for use of additional metrology and process control for semiconductor processing.

Table 4 Future Opportunities & Drivers

- Measurement between steps in multiple-step single wafer processing
  -only chance for measurement is with sensors
- Tool/process start-up/shut-down control
  -ex: importance of plasma damage just beginning to be addressed
- Improved steady state control
  -correlation of yield/faults to noisy behavior suggest tighter real-time steady state control may result in tighter wafer results
- Integrate process, hardware, and control design
  -controllability and observability determined by hardware and process not by control system
- Other sensors for control & monitoring
  -current parameter being used in real-time control loop may not be best variable to control
- Machine process checks without a wafer
  -characterize machine and process during idle times

4.2 過渡的段階

測定データを自動的に集め，適合度を判定し，故障を探しだす。ときにはデータを解析し，設備や工程にフィードバックし，加工中の素材の管理基準を厳しくするために使う。この調整方法には自動方式とスニーカ方式とがある。スニーカ方式とは人間が新たな入力パラメターを手動で調整し直すことをいう。最近は，設備と工程全般にわたりエキスパートシステムが広く利用されつつある。

4.3 今後の展望

自動計測，データ収集，オンラインそして現場測定を積極的に活用し，ウエハ，設備，工程の各レベルにおける状態を把握し工場の管理データとする。これらのデータを設備や工程条件にフィードバックし，リアルタイムな改善や予防保全に役立つ。また，エキスパートやデータを集積し，知識データベース化することにより，より高い信頼性の製品を実現できる。**表4**に将来への推進要因とチャンスを示す。

5. 工程管理の今後の課題

設備，工程，自動化および通信が複雑になるとともにインターフェースが増えるが，これを明確に定義し標準化しないと，アクセスも接続もできない。半導体工場では，各種ツールのモジュール化や クラスタ化をはかってきたが，複雑化，短納期，コストダウンへの要求はますます厳しくなっている。他方，ユーザーは

5. Challenges for the future of process control

More interface layers are added, as complexity of the equipment, process, automation and communication increases. These interfaces must be well defined, and standardized for quick access and “hook-up”. Tools have become more modular and clustered to meet the demands of the process and device requirements. In a similar fashion, system controllers have to become somewhat analogous. Complexity is ever increasing, time-to-market is ever shortening, cost must be contained; additional data is required to maintain current capability. Thus, new things, new data types (such as new sensor hardware), will always need to be tried, and the user needs easy access to the data and the methods they use to turn data into information. And it is not one data stream, it is several. And it is not one analysis methods, it is several. Equipment will become “intelligent” systems and additional metrology and process control are integrated in the system. Table 5 lists some of the business factors that will help tool integration.

Table 5 Business Factors for Integration to Occur

- Business Needs (Drivers) of
  - -IC manufacturer
  - -Equipment supplier
  - -300mm
  - -Shrinking dimensions (e.g., linewidth)
  - -Shrinking die size
  - -Environmental, safety, and health (ESH)
- Integration must be profitable
  - -Increased productivity
  - -Creates a competitive edge
- Integration must be feasible
  - -Hardware/software changes spawned by 300mm (i.e. insertion node)
  - -Availability of commercial sensors & sensor bus
  - -Viability of software suppliers
  - -Emergence of controller consultants/trainers

Software content will continue to increase, and thus improved software quality methods need to be employed. Other industries have employed various levels of process control methods to their manufacturing. The semiconductor industry should learn from these other industries, and adapt what works. As more layers are added to the equipment and process, more business interfaces are also created. So now to complete new development on tools and processes with new metrology and control, to meet customer requirements, you have multi-party relationships instead of two party relationships. The ability to manage multi-party relationships for program success will be a requirement for suppliers in the future.

The National Technology Roadmap for Semiconductors 1997 envisions future metrology to evolve into more integrated systems with the process tools, employing process control methodology. The nature of the business of semiconductors will encourage this integration to occur, for continued improvements for device manufacture.

“The FORD Taurus has more computing power than the orginal Apollo that went to the moon [in 1969].”
Alex Trotman, Ford Motor Co. Chairman & CEO, 1997

迅速で容易なデータ変換を求めている。**表5**に集積化のためのビジネスチャンスを示す。

ソフトウエアは今後も増加し続けるだろうが，ソフトウエアの品質改良を支援することが必要となる。新しい技術や制御方法を開発したり顧客のニーズに応えるためには，二者間ではなく，複数の当事者間での関係を構築することが今後の製造装置メーカーには求めらる。

1997年のNational Technology Roadmap for Semiconductorsは，将来の測定技術が，プロセス制御技術によって工程ツールを組み込んだより集積度の高いシステムへと発展するだろうと予測している。今後も半導体産業は集積化が一層進み，デバイスの製造技術は絶え間なく進歩するだろう。

フォード社のA. Trotman会長はこう言っている。
「フォードのタウラスは1969年に月に行ったアポロと比べはるかに勝る計算能力を備えている」

（抄訳：半導体システム企画開発部 永井良典）

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