In-Stat

In-Depth Analysis

AMD's Advanced Manufacturing Model: Combining Flexibility with Intelligence

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Executive Summary

The cost of developing new semiconductor process technologies and constructing new fabs are driving significant changes in the semiconductor industry. While the number of semiconductor suppliers with fabs continues to shrink, those that continue to manufacture in state-of-the-art fabs have a significant competitive advantage in terms of both cost structure and technology expertise. These increasing costs, however, are forcing new efficiencies in the industry through partnerships in both process development and manufacturing capacity.

For more than a decade, AMD has been working to enhance its efficiencies in semiconductor manufacturing through both design and manufacturing techniques. One such innovation is the development of Automated Precision Manufacturing (APM), a set of tools and processes used for gathering and implementing a constantly growing database of information to help improve and automate semiconductor manufacturing decisions. APM software technologies serve as a kind of "central nervous system" in AMD fabs by forming an integrated fabric of communication and control linkages with the hundreds of tools throughout the plant. APM tools consist of multiple libraries and methodologies, a hardware abstraction framework, and automated decision software that interact to form the backbone of the APM framework.

AMD uses APM to consistently gather information throughout the manufacturing process to develop applications that can optimize the desired characteristics of the final product while efficiently using all available resources, increasing yields, and minimizing waste. The most recent version of APM, enhanced for 300mm production, provides manufacturing flexibility down to the single wafer level. Future enhancements may reduce this further to the die level for optimal manufacturing accuracy, efficiency, and control.

AMD's partners have also benefited from AMD's development of APM technology. Through its foundry relationship with Chartered Semiconductor, AMD licensed Advanced Process Control (APC) components of APM to ensure quality and efficiency in the foundry's production of high-performance microprocessors. The result has been a dramatic increase in efficiency for Chartered, not only in the manufacturing of AMD microprocessors, but also products for other customers that range in both volume and product complexity. According to Chartered, APM implementation has resulted in a change in its culture on process control, improved yields, tighter manufacturing specifications, and shorter ramp schedules.

For AMD and its partners, APM technology has proven a critical element in meeting the challenges of a highly competitive market. Thus far, AMD has limited the transfer of APM to other parties, but the technology is likely to benefit the entire industry through knowledge-sharing with the ecosystem for the development of next-generation equipment and tools.

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Introduction—An Industry Challenge

As the semiconductor industry reaches new levels of integration and innovation, the costs of developing and manufacturing products continues to escalate. Over the past decade, the capital costs associated with constructing and outfitting a new state-of-the-art fab have risen 250%, while the cost of developing process technology has risen roughly 400%. As a result, the remaining semiconductor manufacturers (IDMs) and foundries, along with the rest of the industry, are continually looking for cost-efficiencies.

For new process technology, companies are increasingly banding together to share costs. There are currently three major consortiums, a consortium of Japanese semiconductor manufacturers called Advanced SoC Platform Corporation (ASPLA), a consortium led by IBM, and the Crolles 2 alliance, which will be dissolved by the end of 2007. The IBM consortium is split into two groups focused on bulk CMOS and SOI development. Despite the separation of the development, there is a considerable amount of crossover between the technology and the partner relationships, which now include AMD, Chartered Semiconductor, Freescale, IBM, Infineon, Toshiba, and Sony. The joint process development approach appears to be working well but only addresses one side of the cost equation.

The other side of the equation is the manufacturing. Regardless of whether a company relies on fabs or foundries (or, like AMD, a mix of the two), the ability to rapidly and accurately manufacture in-demand products is a fundamental business problem. Additionally, the goal of every company is to maximize its return on investment (ROI) for its owners/shareholders. In semiconductor manufacturing that means keeping fabs running with orders for new products while maximizing efficiency. Today, there are two models for achieving this goal. Both methods have advantages and disadvantages. The first is a brute force model of building multiple fabs, copying the process technology exactly, and optimizing the products to run on the process. The second model is optimizing the process around the products. AMD uses the "optimizing model" and even goes a step further in making continuous enhancements based on holistic fab data. By optimizing the process to the product, AMD's manufacturing system helps increase manufacturing efficiency, productivity, and flexibility for its entire line of microprocessors.

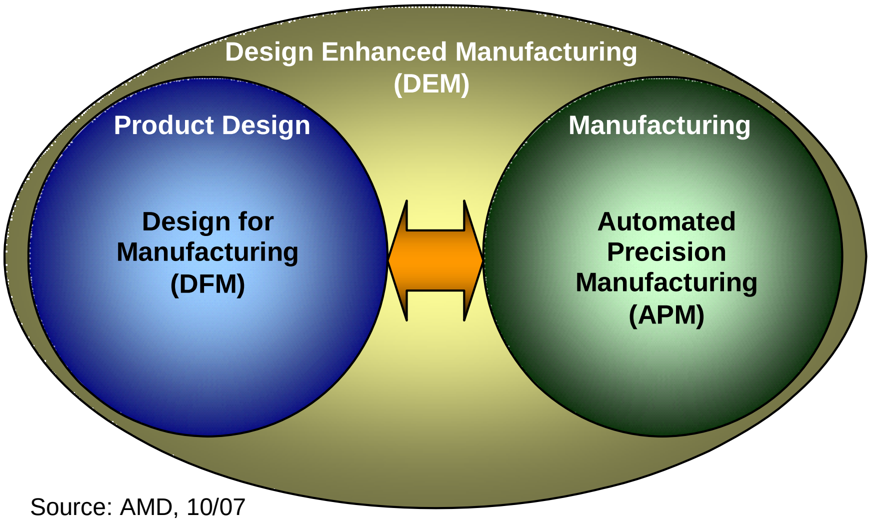
AMD Overview

Although AMD is not the first to transition to new process geometries, AMD has been a leader in many areas: from collaborative transistor development with its partnership with IBM, to being one of the first to volume manufacturing with new technologies, such as copper interconnects and low-*k* dielectrics in 2002, and silicon on insulator (SOI) in 2003. AMD and its partners will also be the first microprocessor manufacturers to begin using immersion lithography at the 45nm process node. All of these firsts have contributed to increases in performance and/or decreases in power that complement AMD's efficient design strategy.

In addition to the process technology, AMD has a cohesive strategy that combines its expertise in semiconductor design and manufacturing called Design Enhanced Manufacturing (DEM). The goal of DEM is to reduce variability in both design and manufacturing for improve yields. To accomplish this goal, DEM combines Design for Manufacturing (DFM) tools in the product design and Automated

Precision Manufacturing (APM) tools to reduce the design tolerances while increasing the control granularity of the manufacturing process (Figure 1). The result is advanced microprocessor designs that are highly manufacturable.

Figure 1. Design Enhanced Manufacturing (DEM) Model



Source: AMD, 10/07

AMD's New Manufacturing Model

Being a small company in a market dominated by a single large competitor requires a level of resourcefulness to remain competitive. AMD is in such a position, and has been very effective in utilizing its manufacturing resources. To remain competitive, AMD has turned to manufacturing smarter versus building a large number of fabs. To accomplish this task, AMD has adopted Lean Manufacturing methodologies (see sidebar) and Automated Precision Manufacturing (APM) to improve control of the manufacturing process while eliminating waste. These methodologies and technologies are proliferating throughout AMD's business and technology partners to improve the efficiency of the entire value chain.

What is APM?

Automated Precision Manufacturing (APM) in its most general sense is a set of tools and processes used for gathering and applying a constantly growing database of information to improve AMD semiconductor manufacturing. To put the amount of information of this database in perspective, consider that AMD has been gathering information to develop APM from almost every possible source since the mid-1990s, including individual steps in process technology, characteristics of each piece of fabrication equipment, and information from each wafer produced. Just considering a baseline of 15,000 wafers per month, the amount of information that can be gathered is astronomical. For other semiconductor manufacturers, this information may only be used temporarily. APM turns all the information into meaningful manufacturing and business decisions by fully utilizing the available IT resources. The tools, however, are the key to APM; they form an integrated fabric of stability, control, and optimization throughout the fab.

Lean Manufacturing

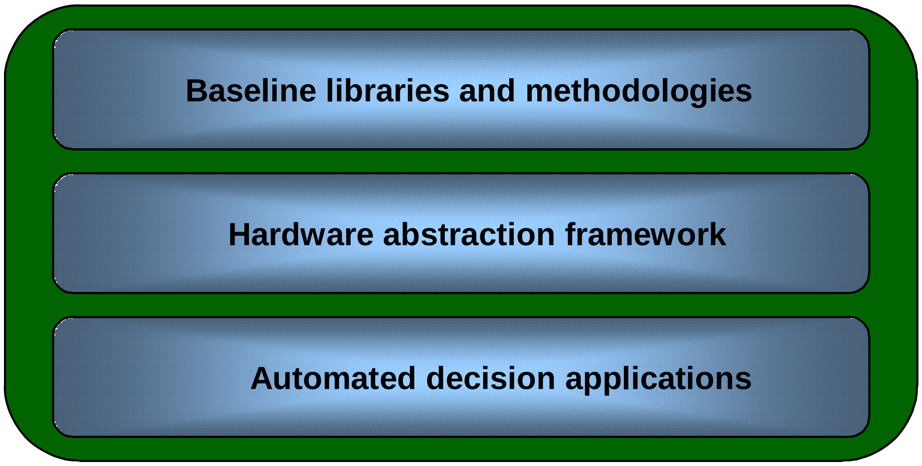
Lean is a methodology employed to continuously increase the efficiency of a process through reducing costs and improving quality. Many of the Lean concepts date back to the beginning of the industrial revolution, but are exemplified in more recent implementations, such as the Toyota Production System (TPS).
The key principles include:

- Just-in-time manufacturing based on actual demand
- Zero defects (or close to zero) through effective problem solving
- Elimination of waste
- Continuous improvement through a circular process of identification, implementation, measurement, and evaluation
- Flexibility in production without sacrificing efficiency
- Value-chain integration through close relationships with suppliers
- Single-defect detection and control (Autonomation)
- Efficient utilization for maximum capacity
- Measurement and control to compare results with expectations

Implementing a Lean methodology requires education of the staff, implementation of processes, regular continuous improvement exercises, and a system to measure and evaluate results in a continuous manner. The benefits of a Lean methodology extend well beyond the process improvement to the effective use of all resources, empowerment of employees, and the development of effective strategies.

In general terms, APM tools consist of libraries and methodologies, a hardware abstraction framework, and automated decision software. For the Advanced Process Control (APC) specific applications discussed in detail in this paper, those are referred to as Baseline, framework systems such as Catalyst, and Applications, respectively (Figure 2). Together with other AMD systems, these resources implement and use the information available about the fab and the metrology of the wafers throughout the manufacturing process to intelligently route and process wafers for optimal yields and performance.

Figure 2. Factory Architecture for Advanced Process Control (APC)



Source: AMD, 10/07

The APM tools are constantly being developed and modified (for example, to meet changing process technology needs node-to-node or for a new piece of fabrication equipment), while continuously improving the process. At each major step, however, AMD adds a new level of control. APM 300 takes the automated receipt control from the lot level to the individual wafer level (Table 1). Theoretically, this could also allow AMD to reduce the size of the wafer lot from 25 to one for a continuous flow manufacturing model. The move to smaller lot sizes is a key component of the company's Lean implementation and is currently in development. AMD also hopes to take the process control to the die level in the future for absolute control of the manufacturing process. APM 300 adds in-line yield prediction of variations that may cause defects, adjusting for them before they occur, and active scheduling capabilities to more effectively route products through the fab based on knowledge of the wafers and the status of tools and other lots in the fab. Designed in tandem with the ramp to 300mm wafers at Fab 36, which is now complete, APM 300 further increases AMD's manufacturing efficiency while reducing costs through the ability to process roughly two and a half times the number of die per wafer compared with the 200mm generation.

Table 1. APM Generations

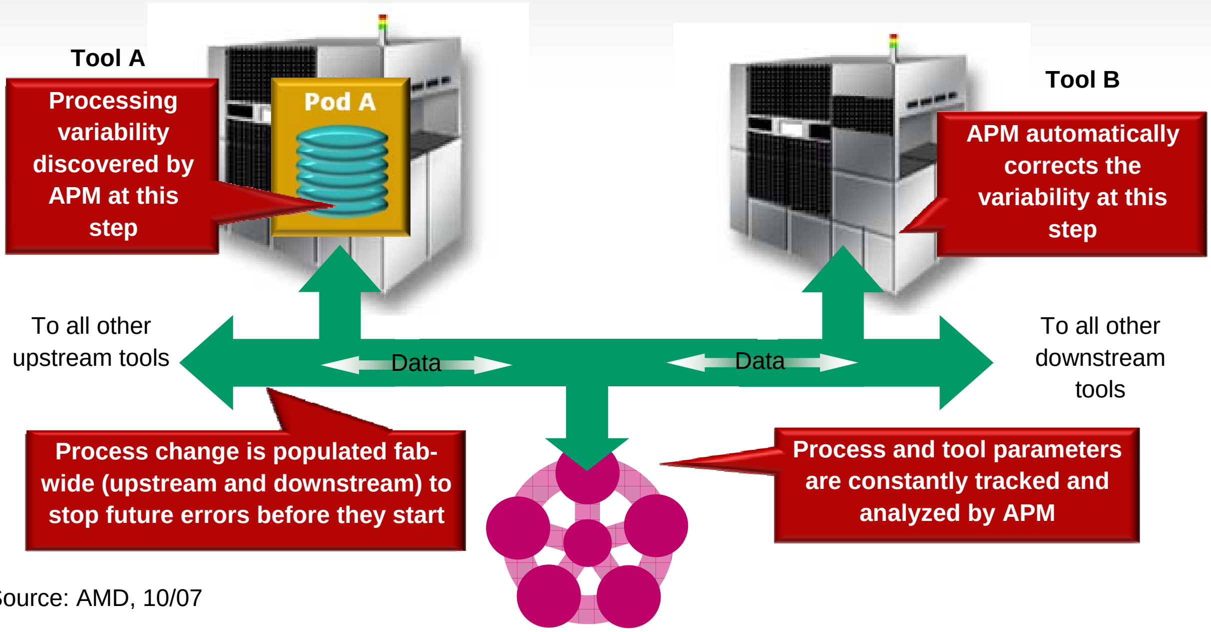
Generation	Enhancements
1.5	• Networked tool interfaces • Centralization of data storage • Basic data-mining capabilities
2.0	• Integrated data analysis • Automated lot level process and work in process (WIP) control • Automated tool and process monitoring
300	• Wafer-level control • In-line yield prediction • Active scheduling

Source: AMD, 10/07

How APM Works

In addition to providing the backbone of information and automation to a wide array of fab tools and functions, APM uses historical information about the process technology and the equipment being used, combined with metrology history of the wafers being processed in both a feed forward and feedback fashion to control the equipment and process at each step (Figure 3). In an ideal manufacturing environment, there would be a single statistical process methodology that would produce a consistent result. In the real-world, however, complex manufacturing environments have greater chances of error. Suppose that a wafer goes through 250 discrete process steps over a period of 90 days from start to finish. If each process step is set to a preset configuration, then even the minutest variation in any given step could be magnified through the process. If multiple steps vary from the statistical mean, the resulting errors could be magnified exponentially. Although this may not mean a defective part, it could result in semiconductors (microprocessors in the case) that yield at lower performance levels or bins, which also results in lower prices and ROI.

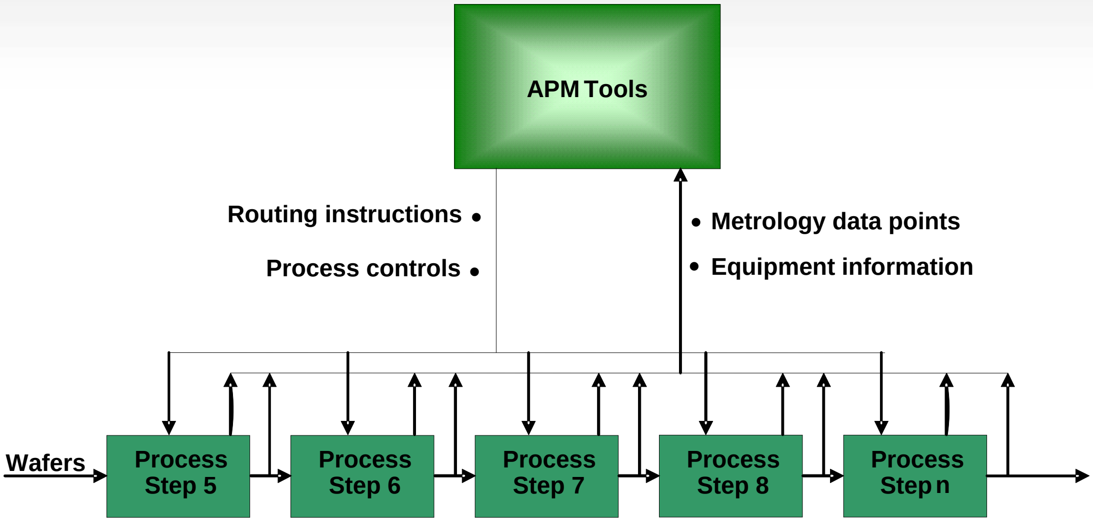
Figure 3. APM Information Flow



Source: AMD, 10/07

APM introduces controlled variation into the process to increase the desired yields. APM uses all the information combined with the software tools to detect, and in some cases predict, potential problems. By looking at the metrology of each wafer and the equipment being used, then combining it through complex algorithms to alter the process of the tool, each wafer may require slightly different process steps, such as differences in the metal layers, bake time, or polishing to achieve the optimal yield. Now consider how complex the process becomes when there are multiple tools that can be used for each step and the settings of each tool may change over time. Even if the same tools are used over the 90 days required to process a wafer lot, the process requirements could be different each time. AMD's APM technology not only optimizes each step but also routes the wafers to the tools that are likely to achieve the desired results. APM also allows for the process to be halted at any time in the process if a potential out-of-band condition is determined on even a single wafer. The result is a highly automated environment that continually learns and adds variations to the process to achieve desired results (Figure 4). The variations also ensure a minimal amount of wasted time and material at each step in the process. While many APC examples have been referenced in this paper, it should be noted that APM tools extend far beyond APC to reach every aspect of the fabrication process.

Figure 4. APM Example

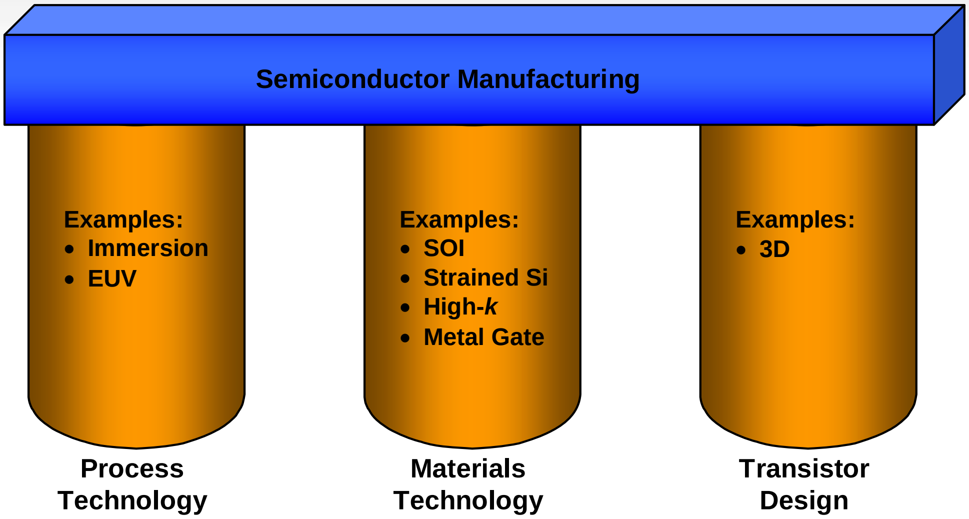


Source: AMD, 10/07

Another key aspect of APM is achieving the results using existing equipment and avoiding extra steps in the manufacturing process. In an ideal scenario, metrology data would be available after each step in the process, but this would increase the process steps and time. As a result, AMD gathers information about multiple steps in the process at a single time and feeds the information both forward to equipment later in the process and back to adjust the settings for other lots.

The APM methodology also allows for subtle differences in equipment, environment and process steps. The ability to change the dynamic of an individual wafer or even a wafer lot is critical. The flexibility allows for the testing of changes on test lots without interrupting the manufacturing flow. This flexibility is also a key component of AMD's manufacturing strategy. Unlike larger semiconductor manufacturers that limit changes to the process at major nodes (130nm, 90nm, 65nm, etc.) or limited sub-nodes, AMD utilizes a series of sub-nodes with each process generation in an effort to continuously improve both the process and product, while minimizing the risk of change. Typically, AMD will have four or more sub-nodes at each manufacture process node. At each sub-node, AMD may introduce a variation into the process to enhance the performance and/or yields of the microprocessors, or to modify any of the three key pillars of semiconductor innovation—process technology, materials technology, and circuit design. AMD has already indicated the move to an immersion lithography process (the first pillar) and high-*k*/metal gate materials (the second pillar) during the 45nm process generation.

Figure 5. Pillars of Semiconductor Innovation



Source: In-Stat, 10/07

AMD has two similar strategies for transistor design changes (the third pillar) referred to as Continuous Transistor Improvement (CTI) and Shared Transistor Technology (STT). CTI allows AMD to make changes to the transistor on a quarterly basis on average, while STT allows AMD to test and verify transistor enhancements before moving to new design geometries associated with the n+1 process node.

Another feature of APM is that it is runs on the Windows operating system, enabling AMD to develop, modify, and maintain the tools while integrating them with other third party software, including SAP, SiView, Camstar InSite, and INCA on MS SQL. The APM suite currently includes over 300 software tools that touch every step in the microprocessor production process.

Benefits of APM

APM offers an increased level of flexibility and control throughout the manufacturing process development, ramp, and production phases. Although ramp rates and yields are determined by many factors, improvement in process control can produce positive results. According to AMD, APM was a contributing factor in the 66% and 44% increase in ramp rates to a mature-yield target at the 130nm SOI and 90nm SOI process nodes, respectively, while the 65nm SOI process began production above the same mature-yield target for new and existing products. Similarly, AMD transitioned to 300mm wafers at its new fab (Fab 36) during the 90nm SOI process node while simultaneously increasing yields.

Extending APM to the Entire Manufacturing Strategy

As indicated earlier, the cost of semiconductor manufacturing is on an exponentially increasing trend. As a result, adding additional fab capacity carries a high risk to semiconductor manufacturers, especially if utilization cannot be immediately maximized. To augment its manufacturing capacity plan, AMD has turned to foundries to balance the cost risk versus the need for additional capacity. AMD currently uses Chartered Semiconductor to manufacture a portion of its microprocessors. With the acquisition of ATI in 2006, AMD adopted foundry relationships with TSMC and UMC for the fabrication of core-logic chipsets and graphics processing units (GPUs).

The relationship with Chartered is a critical element in AMD's strategy for flexible capacity to meet spikes in demand. In similar foundry agreements by other semiconductor IDMs, the foundry is typically used for older generation or non-critical components. The AMD/Chartered agreement is unique in that AMD looks to Chartered for the same state-of-the-art microprocessor produced in its own fabs. To meet the yield and performance expectations, AMD chose to license APC portions of its APM suite to Chartered.

Licensing APM to another partner is not an easy task. Because APM is designed specially for AMD's fabs, integrating APM is more than a technology transfer from one partner to another. Integrating the selected APM elements at Chartered required training the Chartered staff in the methodology, porting the software components to Chartered's manufacturing framework, and modifying applications to different equipment and software solutions. In total, transferring APM to Chartered required a two-year effort by AMD staff, plus on-going technical support and counsel.

Chartered currently has licensed AMD's manufacturing process and 13 APC-focused APM 2.0 and APM 300 tools that are implemented on its 90nm process using 300 wafers at Fab 7 in Singapore. Chartered will begin manufacturing on AMD's 65nm process node by the end of 2007.

According to Chartered, implementing APM resulted in a change in Chartered's process control culture, improved yields, tighter manufacturing specifications, and shorter ramp schedules. According to figures supplied by AMD and Chartered, implementing APM has resulted in preliminary efficiencies at each step of the fabrication process, including a more than 65% improvement in lithography overlay process and more than a 66% reduction in defects for Cu residue in the CMP process (Table 2).

Table 2. Fabrication Step Improvements

Module	APM Benefit
Litho	Overlay/DICD Cpk improved > 65% Litho CD/overlay OOS related rework reduced by > 43% Auto 3 (SiView) production efficiency improved by 10%
Etch	Cpk improved by > 35%
CMP	Defect reduction in Cu residue by > 66%

Source: Chartered Semiconductor, 10/07

The benefits of APM also extend to the many resources involved in the fabrication process ranging from greater efficiencies in chemicals to equipment and engineering resources (Table 3). Although the overall yield improvement may appear to be only 1%, this figure results from just a single application (copper CMP RtR control) and is multiplied by the capacity of the fab plus the potential for several thousand more wafers resulting from the increased process efficiencies. These gains represent just a small fraction of yield improvement since several applications were implemented at numerous critical operations.

Table 3. Efficiencies from APM

Process Enhancement	Gain
Chemical usage reduction (BTA)	> 70%
Yield Improvement	~ 1%
Equipment productivity improvement	~ 1%
Enginnering productivity improvement	~ 2.9%

Source: AMD & Chartered Semiconductor, 10/07

The value of APM to Chartered reaches well beyond the capability to meet the demand for AMD microprocessors. As a manufacturer for other semiconductor companies, including Infineon and Qualcomm, Chartered is able to use the knowledge it has gained and the tools to benefit all its customers. According to Chartered, APM has resulted in improved results with all products and all sized manufacturing lots. Likewise, APM could be used to enhance the manufacturing of AMD's core-logic and GPU products at TSMC and UMC in the future.

Far-Reaching Effects

To AMD, APM is a critical element in fulfilling the needs of its customers while remaining competitive in the market. The effects of APM, however, are far-reaching. Although AMD selectively licenses APM technology to partners, the concept is focused on measurable results from information received at every possible point in the manufacturing process. As a result, the information naturally flows to other fab resources, including the factory automation and materials handling systems, as well as the staff that are responsible for maintaining and continually improving the process. AMD's participation in the joint development of future process technologies and requirements for new tools and equipment indirectly feeds results of the APM throughout the ecosystem.

Conclusion

Just as developing a successful corporate strategy requires the consideration of all factors that may influence the outcome, APM technology is a component to AMD's manufacturing strategy and the company's success in a highly competitive market. Although all semiconductor manufacturers use some form of factory automation tools developed internally or from third-party suppliers, AMD has focused on developing its own factory automation to remain competitive in delivering high-performance microprocessors.

The use of APM technology has created a growing knowledge base that can be used to enhance control and automate decisions in the manufacturing process, while increasing the value of the final product, improving the efficiency of resources, and reducing the waste.

The value of APM also extends well beyond AMD to the entire semiconductor manufacturing ecosystem and particularly AMD's current and potential partners in process development and manufacturing. Thus far, only one of AMD's foundry partners, Chartered Semiconductor, has licensed AMD's APM technology, but the same technology could be used at TSMC and UMC, which currently manufacture all products for the company's recently acquired Graphics Products Group.

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