APPLIED Co$t MODELING

Information Exchange For Your Application & Use of Cost Modeling

Volume 12. Issue 1

Inside

Fall 2005

ISSN 1094-9739

Cost of Ownership and the Introduction of New Materials in the Wafer Fab

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<u>Overview</u>

This paper looks at a number of issues revolving around the introduction of new materials into semiconductor manufacturing. Specifically, we examine what are the issues driving these introductions and what are the potential cost of ownership (COO) impacts. Further, this paper presents two case studies to highlight intuitive and unintuitive results.

<u>Why Introduce a New Material?</u>

There are several reasons to introduce a new material into manufacturing. One of the most important factors is environmental, safety, & health (ESH) concerns. This area includes the need to reduce or eliminate the use of or exposure to toxic or dangerous materials. This was the driving reason for the elimination of organic solvent based photoresist developers and replacing them with aqueous developers. Another driver is the need to replace a material that is being withdrawn from the market for other EHS issues, such as C_2F_6. Lastly, there may be a need to achieve compliance with regulations, standards, and guidelines as is the case with the elimination of lead solders from packaging and assembly operations.

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Editorial Board

Publisher

Published quarterly by:

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Calendar of Events

December

4-7 **Winter Simulation Conference**
Lake Buena Vista, FL

7-9 **SEMICON Japan**
Tokyo, Japan

January 2006

8-11 **Industry Strategic Symposium (ISS)**
Half Moon Bay, CA

10-13 **Emerging Technologies -Nanoelectronics**
Singapore

11-13 **Strategic Materials Conference (SMC)**
Half Moon Bay, CA

February 2006

5-9 **International Solid-State Circuits Conference - (ISSCC)**
San Francisco, CA

8-10 **SEMICON Korea**
Seoul, Korea

12-14 **Industry Strategic Symposium**
Amsterdam, The Netherlands

March 2006

21-23 **SEMICON China**
Shanghai, China

28-30 **FPD China**
Shanghai, China

April 2006

21-23 **SEMICON Europa**
Munich, Germany

A second driving force is process cost reduction. This can potentially be achieved through process simplification, die shrinks, and process step cost reductions. One example of process simplification is the use of a patternable polyimide which replaces several lithographic, etch, and clean steps. This example is examined later in the first case study.

Die shrinks typically allow for process cost reductions through the incorporation of more die per wafer. Since costs are more likely to be driven by wafer size and not die per wafer, in most cases die shrinks result in a lower cost per die. Lastly, we can look at each process step individually and seek ways to improve manufacturing costs. An example of this would be the introduction of lower cost materials for use in barrier and seed layers.

Another reason to introduce new materials is to drive device performance improvements. This can be achieved through transistor gate length reduction by moving to the next technology node, introducing a metal gate dielectric stack, or the use of high κ dielectrics. RC time constant improvement is another area that can be assisted by new materials such as moving to copper interconnects and using of low κ materials. It is also possible to reduce current leakage by using silicon-on-insulator (SOI).

Lastly, new materials can assist in improvements in manufacturability (yield & reliability). Manufacturability can be improved through process step elimination or consolidation, such as the previously cited example of photoactive polyimide. The use of more controllable materials can lead to the elimination of non-value-added steps such as metrology and inspection.

Other examples of ways to improve manufacturability include replacing aluminum with copper to reduce electromigration, introducing new materials that can replace several existing materials, and using materials with lower exposure dose requirements or faster etch/depositions rates.

<u>Potential COO Impacts</u>

There are several areas that new materials can impact the COO of the process steps. The first is to look at the impact on the manufacturing equipment. Does the material have an effect on throughput, availability, or other equipment and material handling costs as is required for some copper precursors that require refrigeration?

What is the cost of the material itself? This includes the purchase price, shelf life and material handling precautions, waste treatment of any effluent, and the cost of other materials needed to support the new material such as changes to etchants and cleaning agents.

Perhaps most importantly, how does the new material fit into the technology roadmap? Can a material change allow fixed costs such as capital equipment and process development to be allocated to more than one node?

<u>Case Study #1: Photoactive vs. Non-Photoactive Polyimide Process</u>

This case study uses an older set of process examples to illustrate the potentially unintuitive results from process simplification. While the technology nodes are out of date, the potential outcomes are still valid.

The history of the process changes start at the 1 mega-bit level and the use of an extremely simple passivation process utilizing photoactive polyimide as depicted in Figure 1.

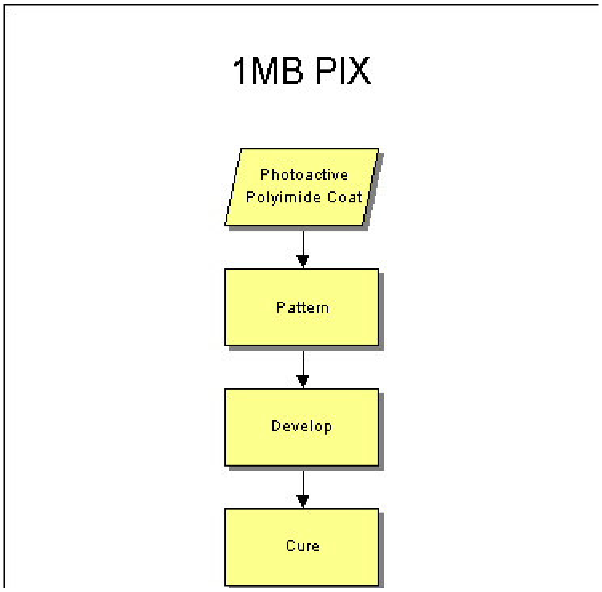

Figure 1: Photoactive Polyimide Process

The tool set employed was a TEL Mark II Track, Nikon Stepper, and SVG Vertical Furnace.

When the process needed to migrate to the 4 mega-bit node, the photoactive polyimide material could not meet the technical specifications and the process was changed to use non-photoactive polyimide at the expense of process complexity (see Figure 2).

The 4 mega-bit process was nearly twice as long but was able to make use of the same tool group. While cost reduction through process simplification was not apparently achievable, at least there was a leverage of fixed costs over multiple technology nodes.

At the 16 mega-bit node, both material types (PIX and PIQ) were available and able to meet the technical specifications. So, what to do? The initial plan was to take the obvious route back to PIX since it achieved process simplification. However, the engineering staff had access to cost of ownership modeling tools that allowed them to determine the true costs differences between these processes.

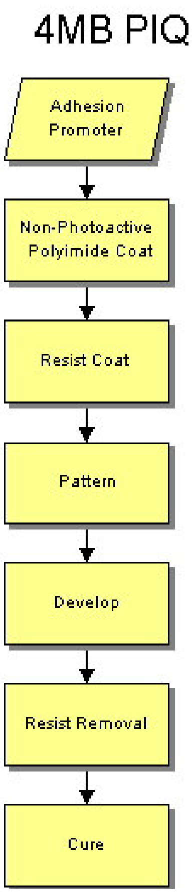

Figure 2: Non-Photoactive Polyimide Process

<u>Results</u>

PIQ adhesion, polyimide, and resist materials were less expensive than the PIX polyimide. Including track throughput showed the PIX process was 1.7x more expensive in these areas of comparison. At the exposure step PIX turned out to be a very poor photoresist with an exposure time of 750ms compared to the photoresist used in the PIQ process at 350ms.

PIX did have a cost advantage at the develop step where the supporting materials were less costly to purchase and had a higher throughput. Additionally, the PIX process required no resist removal. However, at the cure step, the inherent compromise of the PIX material showed itself again with a cure time of 10 hours compared to 7 hours for PIQ.

The net result was that the PIX process was $29.35 compared to the PIQ process of $27.43.

Case Study #2: Copper/Low κ vs. Aluminum Interconnect

In this case study we examine the process and equipment changes necessitated by the move from aluminum to copper interconnects. For reference purposes, Figures 3 and 4 outline a single metal line/via loop for a 180nm Al and 130nm Cu process.

Examining these processes shows the following changes per loop:

- Primary materials changed - 2
- Processing chemicals changed - 7+
- Types of equipment changed - 4
- Process recipes changed - 9+
- Mask changes - 2+
- Al layers replaced by 1 Cu Layer - 1.1 – 1.3

The factors impacting process costs include:

- New capital equipment costs
- Throughput changes
- Process material consumption changes
- Labor and maintenance costs
- Yields

Both processes have cost advantages at the qualitative level. For copper, it requires fewer layers for the same level of performance, electroplating is a lower cost deposition method than CVD or PVD, and it uses Damascene structures.

Aluminum is a simpler process with a well understood equipment set and process capabilities. The cycles of learning for aluminum processes spans decades.

Given the competing factors, it is not obvious which process would have the lower cost, or by how much. To fully investigate the cost deltas, we used Factory Commander®, WWK's cost and resource planning software platform, to model both processes. The results are summarized in Table 1.

	Copper	Aluminum
Number of process steps per loop	36	33
Relative cost of a single layer for a 6 layer process	6.5% of total wafer cost	8.1% of total wafer cost
Layers required for equivalent performance	4	6
Total cost impact	26%	48.6%

Table 1: Cu vs. Al Cost Impacts

While on the surface it appears that the Cu process is more complex, when you examine the performance per layer you find that Cu can provide equal performance with fewer metal loops or increase chip performance for the same number of metal loops. As a result, each Cu loop represents a 1.6% cost advantage. When adding the performance differences requiring more Al loops, there is almost a 2x cost advantage to the Cu process.

ISSN 1094-9739

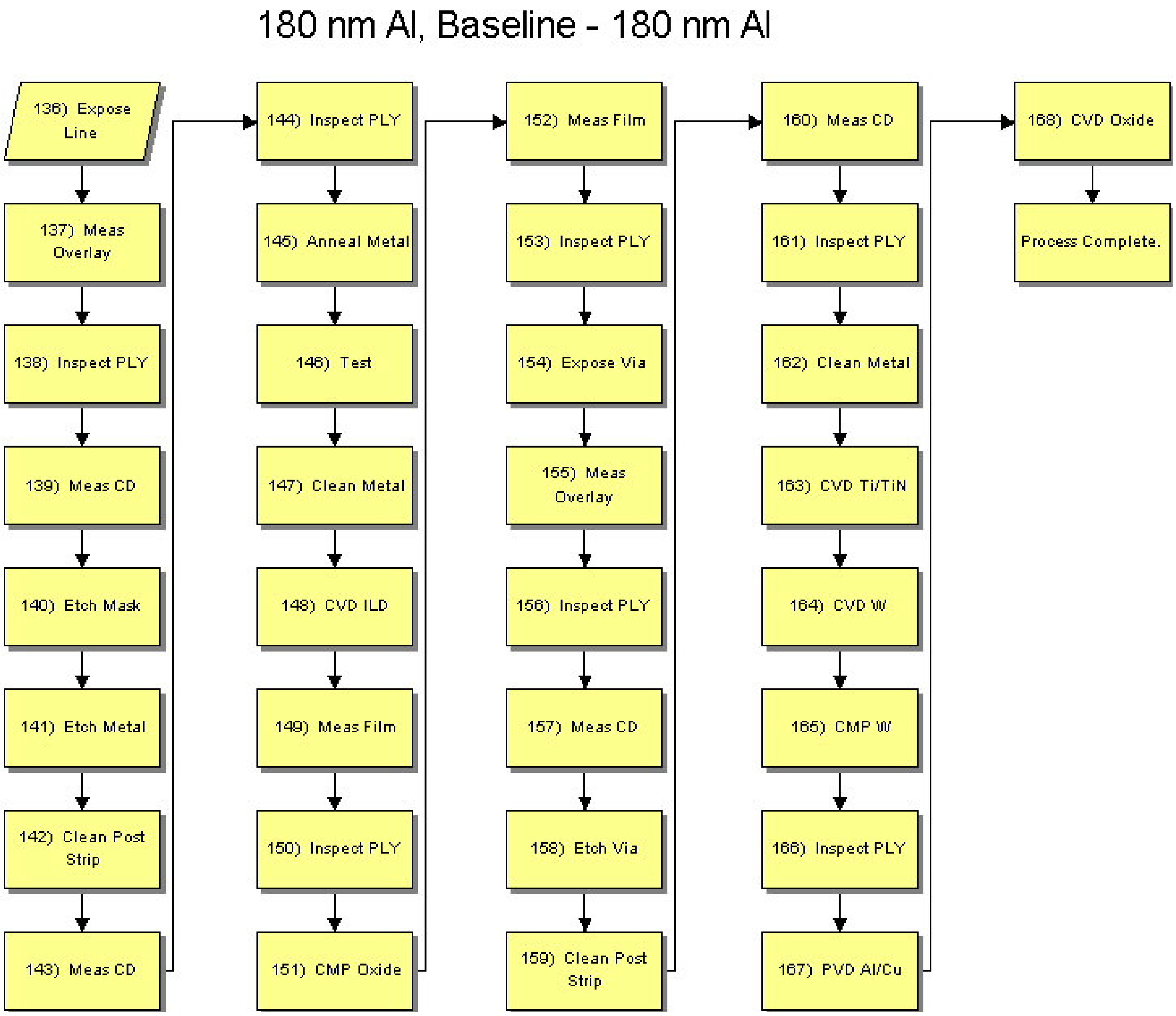

Figure 3: 180nm Aluminum Line/Via Loop

Conclusions

While there are a number of reasons to consider new materials in semiconductor manufacturing (ESH concerns, process cost reduction, device performance improvements, and manufacturability), the anticipated costs results may not be as initially expected. The complicating factor that must be considered is that a single material typically impacts multiple process steps. The resultant line balance considerations for impacts on bottlenecks and near bottlenecks must be considered to fully understand whether an apparently simpler processes flow is truly a lower cost flow.

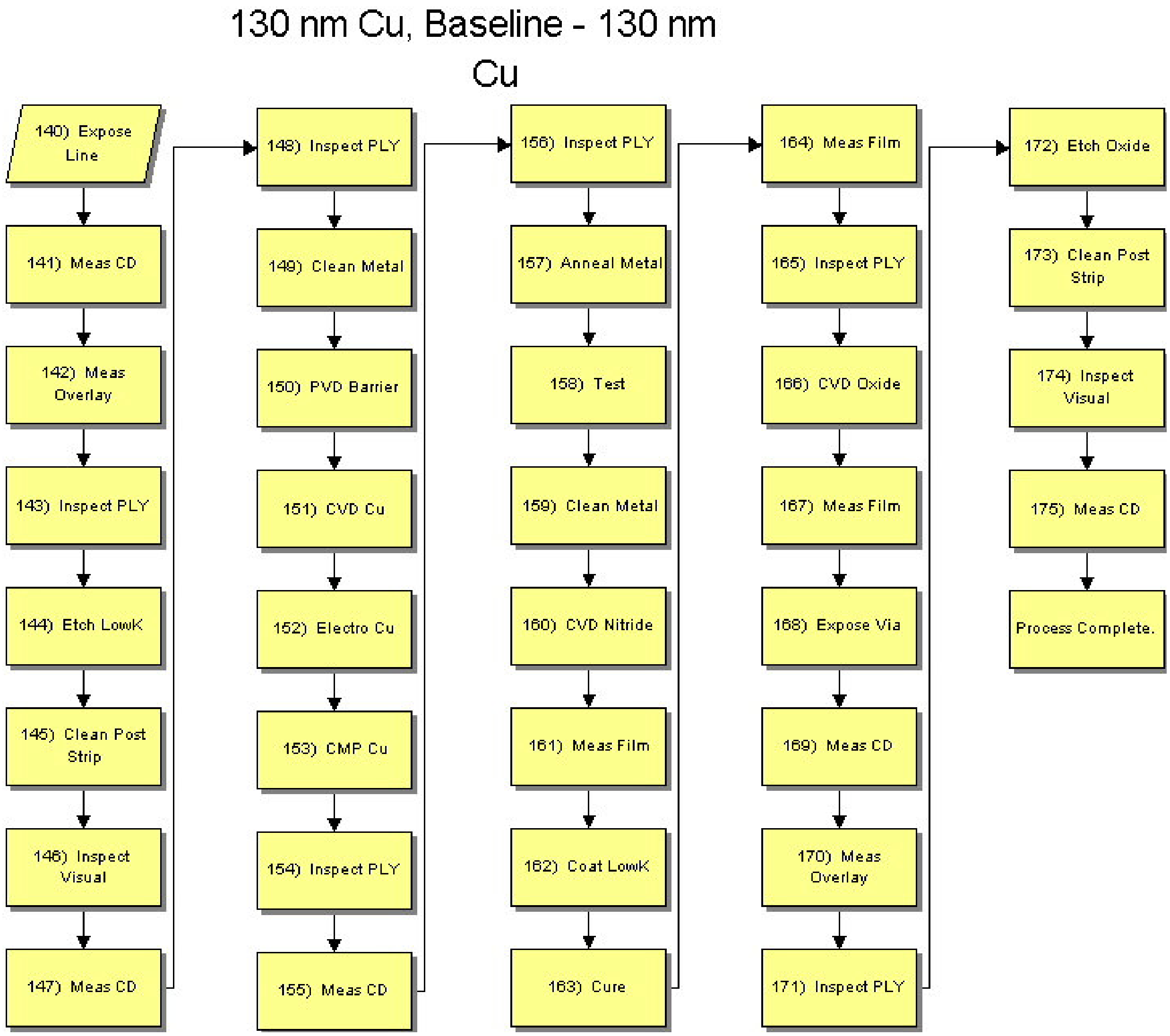

Figure 4: 130nm Copper Line/Via Loop

AMHS Cost of Ownership and Return on Investment using Factory Commander®

David Lauben
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This is a generalized approach for estimating the cost of ownership (COO) and return on investment of a semiconductor manufacturing process where automated material handling system (AMHS) costs are considered. This approach makes use of WWK's Factory Commander® (FC), a cost and resource evaluation program, as the modeling platform of choice. FC is the best choice for this purpose because a full process flow should be modeled, not just selected steps in the operation. Since AMHS COO does not require an analysis of process cycle times, there is no need for discrete event simulation, such as Factory Explorer®.

AMHS COO is estimated from a comparison between two models: one with and one without AMHS. These two models provide a consistent cost comparison and show the system's first order benefits. For simplification, we will limit this discussion to a single product, and let that product be representative of all factory production (i.e. all production starts are included in this product). The primary metric of comparison is the cost per good wafer out at the end of the process, or the product's cost of ownership.

For the model without AMHS, a baseline generic process of IC manufacturing should be used. This model should be a full cost representation and include tool capital, equipment throughputs and availabilities, material assignments and cost, operational labor assignments and salaries, yields, and facility costs. Unless the prospective client requires their specific factory process data be used, the most efficient approach is to start with one of the WWK FC standard semiconductor models. The baseline model may need modification to represent a manual or non-automated material handling environment.

A second model should be created from the baseline model that includes the major costs and benefits associated with the AMHS. The data for this model should represent the general capacity and cost aspects of the specific AMHS. The data should naturally come from credible sources, such as the AMHS supplier or IC manufacturer in which the AMHS is to be installed or is currently in use. In particular, the cost and known productivity inputs (yield improvements, process throughputs, tool availabilities, operator availabilities and utilizations, etc.) will be required for approximating cost contributions. Return on investment may then be estimated from the following equation:

$$ROI = \frac{COO_{Without\ AMHS} - COO_{With\ AMHS}}{AMHS\ Investment}$$

An AMHS for a manufacturing process can be represented either as multiple steps throughout the process or as a single combined representative step that is typically added at the end of the process flow. The latter approach is the simplest option and best if a quick, first order COO estimate is the requirement. Though not as detailed, especially for the modeling of AMHS capacity, this method can still result in a reasonably representative model of the costs involved. Using a combined representative step will have the total AMHS expenditures represented in a single aggregated tool group. This simpler approach should provide sufficiently accurate results for the system cost provided the product volumes do not vary significantly for different what-if scenarios related to production demand.

If the multiple-step approach is used, the model will require the addition of steps to represent the AMHS actions and components. Each step will be specific to one or more AMHS requirements and will require assignment of individual uses of the components as specific, pre-defined tool groups.

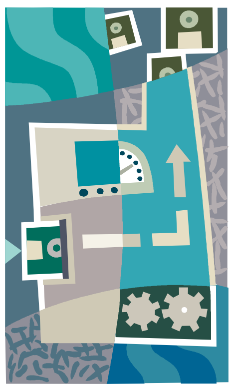
Some AMHS benefits represented in the model include:

1. Fewer damaged wafers transported from one processing station to the next. This is represented in FC as higher equipment (step) yields at one or more steps in the process. The AHMS model would have higher yields at the step(s) where this system is employed.
2. Reduction of wafer misprocessing. This means that the right wafer is transported to the right location at the right time. This is also represented in FC as higher equipment (step) yields at one or more steps in the process.
3. Improved operational labor utilization and productivity. This benefit comes from the operation focusing more on value-added operations rather than product transport. This is represented as both lower labor requirements for equipment and higher labor usage factors. For example, in a true "lights-out" factory, the direct labor component of COO would be zero.
4. Higher rate of throughput for wafers moving throughout in the factory. This can be represented by changing the process throughput inputs for those operations in the process that use of the AMHS. This benefit is more difficult to approximate accurately and requires greater knowledge of the AMHS-specific throughput benefits at those operations.

The other specifics, such as transport frequencies, cost efficiencies, or facility utilization or expansion advantages, will need to be addressed on a case by case basis and in follow-on analyses as specifically requested by the client.

Finally, a frequent question is "Why can't I do this analysis in a spreadsheet." While it can be done, it is not without difficulties. Spreadsheets make for good data collection and organizing environments and they can be used to some extent to make calculations and do output reporting. However, they make poor relational databases and are fundamentally lacking as modeling environments. There are two main shortcomings: The first is that the model's linked relationships between data, i.e. cell linkages, in practice are almost always wrong or missing, especially when the spreadsheet is large and complex, or if it has to be modified repeatedly over time. This leads to inaccuracies and suspect results. The second is that they become difficult to use effectively, especially when doing "what-if" analyses. Each assumption is a change to the model that requires alteration of the spreadsheet to accommodate the change, and this often leads to excessive time investments, frustration, and errors.

The modeling of AMHS requires a systematic approach. To properly evaluate COO and ROI, you need to base the analysis on a full process model of a semiconductor manufacturing operation. Since these processes are complex with many modeling entities (tools, process steps, labor, materials, etc.) which tend to be highly cross-relational, it is important that a suitable modeling environment be used. Factory Commander® is designed for this task. For semiconductor AMHS, this software tool enables the user to focus on the value-added tasks of the analysis and provides faster and more accurate results in less time and for less money.



Wright Williams & Kelly, Inc. Releases Factory Commander® v3.1

The world's leading Cost & Resource Modeling (CRM) software increases functionality and ease of use

Wright Williams & Kelly, Inc. (WWK), a cost & productivity management software and consulting services company, announced today the release of a new version of its Cost and Resource Modeling (CRM) software, Factory Commander® v3.1. The latest additions to this powerful financial and capacity planning package further distance itself from passé approaches such as internally developed complex spreadsheets.

A sampling of the many new features added to Factory Commander® v3.1 includes:

- Multi-variable sensitivity analysis
- Improved legacy/spreadsheet data import/export
- Lifetime average costs in addition to specific time periods
- Expanded tool group upgrade capital inputs for periods before t=zero
- Support-tool assignment at process steps
- Shift teams added for labor groups

The decision making process surrounding new facilities or product lines requires the operation's cost structure and cash requirements to be accurately evaluated. Product pricing, product mix, and production ramp rates are just a few of the many considerations facing strategic planners. Factory Commander® is a cost and resource modeling software platform that provides a fast and efficient method to reduce decision risk and uncertainty. Because Factory Commander® relies on Activity Based Cost Management (ABCM) principles, it effectively identifies the major activities that drive product costs. By providing high-level economic projections such as income and cash flow statements, senior management is able to anticipate market and cost drivers and make accurate strategic decisions based on a strong analytic foundation.

"This latest release of Factory Commander® further demonstrates WWK's long standing commitment to deliver premier products based on client direction," stated David W. Jimenez, WWK co-founder and President. "For more than a decade, our relationship with Sandia National Labs, the original IP holder for the basis of Factory Commander and the transition of their chief software architect to WWK has led to our ability to rapidly address market requirements. We look forward to continuing our leadership position in this unique software arena."

Wright Williams & Kelly, Inc. Offers Real Wafer Fab Cost Benchmarks

Clients Agree to Share Actual Fab-wide Cost Data

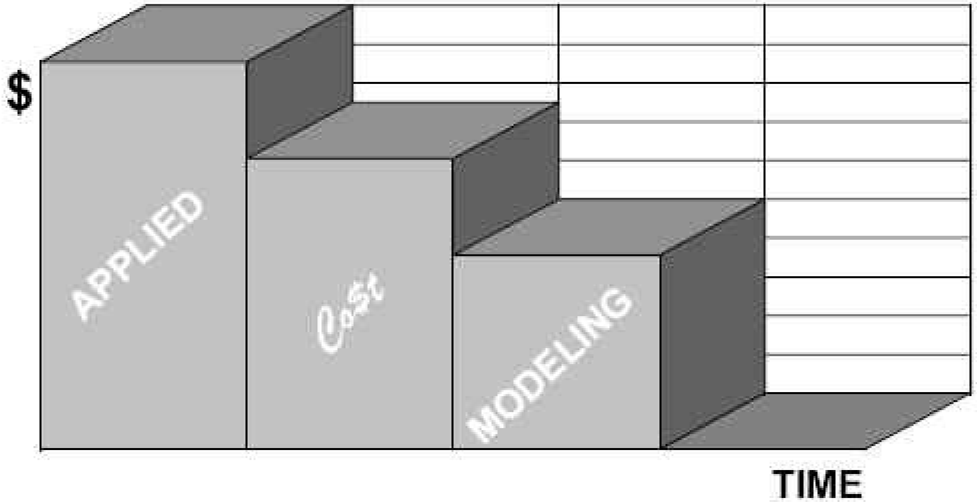
November 30, 2005 (Pleasanton, CA) – Wright Williams & Kelly, Inc. (WWK), a cost & productivity management software and consulting services company, announced today the kick off of its confidential wafer fab cost benchmarks database, *Mercury CS*™ . These cost benchmarks contain actual data from wafer fabs operating at target nodes between 130nm and 65nm at both 200 and 300mm wafer sizes. Projected costs at 45nm are also targeted for early 2006. Early program entrants will receive a substantial discount for their participation.

WWK's data collection approach is based on a consistent methodology utilizing Factory Commander® cost & resource modeling software. Participating clients have their high level cost data (cost per wafer, module, and loop) anonymously added to WWK's *Mercury CS*™ database. In exchange, clients gain an unprecedented insight into benchmark data and individual areas of opportunity for cost reductions. *Mercury CS*™ provides the ability to sort cost data by wafer size, technology node, and product type. Output cost data includes minimum, maximum and average results. Program participation is limited to IDM's and foundries operating wafer fabs in the listed node and wafer size regime.

"WWK has been approached by our clients indicating a strong need for apples-to-apples cost data," stated David W. Jimenez, WWK President. "Currently available benchmarks based on surveys have too many assumptions from non-user data to be the basis for billion dollar decisions. WWK's strength is that we do the cost modeling utilizing standardized methodologies and commercially available Factory Commander® software. The advantages of this approach are so overwhelming that our clients have agreed to anonymously add their operating costs to *Mercury CS*™ in exchange for a better understanding of where they truly fit in the world of low cost manufacturing."

With more than 3,000 users worldwide, Wright Williams & Kelly, Inc. is the largest privately held operational cost management software and consulting company serving technology-dependent and technology-driven organizations. WWK maintains long-term relationships with prominent industry resources including International SEMATECH, SELETE, Semiconductor Equipment and Materials International (SEMI), and national labs and universities. Its client base includes nearly all of the top 20 semiconductor manufacturers and equipment and materials suppliers as well as leaders in nano-technology, MEMS, thin film record heads, magnetic media, flat panel displays, and solar panels.

WWK's product line includes TWO COOL® for detailed process step level cost of ownership (COO) and overall equipment efficiency (OEE), PRO COOL® for process flow and test cell costing, Factory Commander® for full factory capacity analysis and activity based costing, and Factory Explorer® for cycle time reduction and WIP planning. Additionally, WWK offers a highly flexible product management software package that helps sales forces eliminate errors in product configuration and quotation processes.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