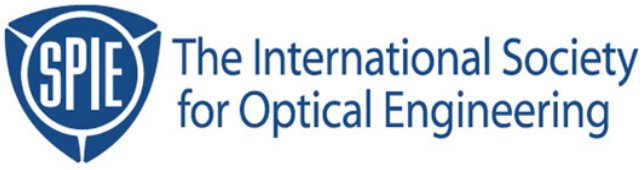

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Cost analysis of lithographic characterization: an overview

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Abstract

The traditional cost of ownership approach used in the semiconductor industry answers the question "How much does processing a test wafer increase the cost of product?" However, this approach does not directly answer the question "How much does it cost to process a test wafer?" A simple new cost of ownership model which answers this question, the Opportunity Cost Model (OCM), has been developed and is presented here. Background information on the OCM, the determination of opportunity costs, and the extra costs associated with test wafers are analyzed. Also, in an effort to quantify the costs associated with test wafer processing, a comparison of modeling and test wafer processing is presented.

I. Introduction

The processing of test wafers is an essential part of the operation of any semiconductor manufacturing facility. From process development, to equipment and material qualification, to process optimization and maintenance, test wafers provide the most common means for obtaining lithographic characterization data. Despite the familiarity and (often high) volume of test wafers, most lithographers have very little idea of the costs associated with the processing of these wafers. In most semiconductor fabrication facilities these costs are skyrocketing. This is due to factors such as increased process complexity and costs and, in many cases, increased wafer size. As a result, companies which analyze and minimize the costs associated with test wafer processing will help to ensure their positions in the competitive semiconductor industry.

Given that the processing of test wafers provides critical information to semiconductor manufacturers, complete elimination of this processing is not viable in the immediate future. However, knowing the costs associated with processing test wafers, controlling these costs and using all available alternatives to make the most of the limited resources a manufacturer has at their disposal will allow manufacturers who "process smart" to make the best decisions possible, keep manufacturing costs low, and gain competitive advantage in the marketplace.

II. Traditional Cost of Ownership Approach

Examining the costs associated with processing wafers provides a reference point regarding where manufacturers' limited resources are being spent. Additionally, this type of analysis provides information on how these resources might be used more creatively and innovatively in achieving an

organization's goals. In considering the costs associated with processing wafers, there are two basic types that are relevant: *variable costs* and *fixed costs*. Both variable costs, which typically include all material and labor costs, and fixed costs, which typically include all overhead costs, are defined in terms of how, based on changes in the volume of a chosen cost objective, the total cost is altered. Variable costs change total cost in direct proportion to changes in total volume. For example, if processing wafers costs a manufacturer $2,000 per wafer, and the manufacturer processes 25 wafers, then the total wafer processing cost is $50,000. Should the manufacturer decide to run 50 wafers, the total wafer processing cost would be $100,000. Fixed costs are independent of changes in total volume. That is, a manufacturer may pay $10M annually for items including rent, capital equipment purchases, management payroll, property taxes, and insurance. Regardless of the number of wafers run, this $10M does not change. However, this fixed cost does decrease on a per wafer basis as the number of wafers processed increases.

The work of Carnes and Su [1] on long term cost of ownership resulted in the following basic algorithm for their cost model:

$$Cost/Wafer = \frac{Fixed\ Costs + Variable\ Costs}{Throughput + Mechanical\ Thruput\ Yield + Utilization\ Capability} + Cost\ Due\ to\ Yield\ Loss \quad (1)$$

This model bases overall cost per wafer on the actual production time available on a piece of manufacturing equipment [1]. The Equipment States Stack Chart of SEMI's E10-90 guideline, as shown in Figure 1 below, defines production time as:

$$Production\ Time = Total\ Time - (Scheduled\ \&\ Unscheduled\ Downtime + Standby\ \&\ Engineering\ Time + Non\text{-}Scheduled\ Time + Production\ Test\ Time) \quad (2)$$

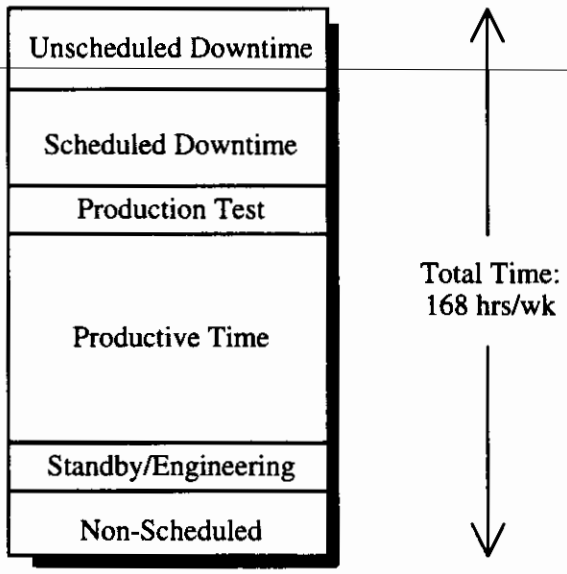

Figure 1. A portion of the Equipment States Stack Chart, SEMI E10-90 Guideline [1].

Obviously, any time spent on the processing of test wafers decreases the available time for processing actual product wafers. In the terminology of the traditional cost of ownership model, any time spent on the processing of test wafers decreases the *production utilization capability*, and the cost per product wafer increases. This simple result indicates the well known need for manufacturers to "process smart" and ensure that test wafer processing is kept to a minimum while product wafer processing is maximized.

As can be seen from the above description of the traditional cost of ownership approach and SEMI's E10-90 guideline, the question "How much does processing a test wafer increase the cost of product?" is answered. However, the question "How much does it cost to process a test wafer?" is left unanswered. In addition, the cost of ownership data required to perform a traditional analysis is not always readily available to lithographers. Therefore, a new model which addresses these issues was developed in order to provide information key to the processing of test wafers.

III. New Opportunity Cost Model (OCM)

A. Background

The Opportunity Cost Model (OCM) is a simple new cost of ownership model developed by the authors to answer the question "How much does it cost to process a test wafer?" This new approach does not involve basic research or innovation, but rather, involves the extension of existing techniques and available information. The goal is to create a methodology for evaluating test wafer costs that can be used by lithographers. Based on the OCM, the total cost of processing a test wafer is given by:

$$Test\ Wafer\ Cost = Opportunity\ Costs + Extra\ Processing\ Costs \tag{3}$$

where the opportunity costs are equal to all normal costs associated with processing product wafers plus profit, and the extra processing costs are those costs incurred which are not normally associated with product wafer processing. These two components of the OCM will be discussed in more detail in the sections below.

The Opportunity Cost Model given by equation (3) makes one important assumption: that the fabrication facility is running at full capacity, which of course assumes that there is a market for the product being manufactured. Thus, when production is temporarily halted to run a test wafer the product that was not made represents lost revenue, which is called the *opportunity cost*. The main advantage of this approach is that the opportunity costs are often already known and well documented for each product in the fab.

The OCM allows lithographers to obtain cost of ownership information for the test wafers processed in the fabrication facility. Rather than having a company's accounting department be solely responsible for determining product profitability, the OCM allows lithographers to be intimately involved in the determination of how their functional area can increase or decrease their organization's

profitability. This information provides lithographers with knowledge which allows for more well-informed, accurate strategic decisions to be made. The following two sections describe how values are obtained for opportunity and extra processing costs.

B. Determining Opportunity Costs

Opportunity costs are defined as the maximum contributions sacrificed when scarce resources are used for a purpose other than producing product. Therefore, the question to be asked when considering opportunity costs is "How much money was *not made* by running a test wafer instead of a product wafer?" The answer to this question depends on the type of manufacturing flow used. For example, consider a completely serial manufacturing process made up of a number of steps. Since each step depends on the output of the previous step, the rate at which output is produced is determined by the slowest step. Processing steps after the slowest step do not affect output rate. If one were to assume that the lithography step was the rate limiting process step (not an unreasonable assumption), then the opportunity cost associated with not running one wafer through this rate limiting step would be the value of a completed wafer. This example represents the extreme maximum possible opportunity cost (and results in a very inefficient manufacturing process).

At the other extreme, consider a manufacturing operation in which every step has many parallel paths (e.g., multiple steppers). If the number of parallel paths is very large, the opportunity cost is given by just the value added to the wafer by that one step. This example represents the extreme minimum possible opportunity cost and clearly shows the value of high volume in driving down costs. Actual fabs operate with some, but not an infinite number of, parallel paths. As a result, the opportunity cost is usually somewhat higher than the "value added" by that particular step. However, to make the analysis as simple as possible, and to give a conservative estimate of the cost of a test wafer, the value added by the lithography step can be used as a first-order estimate of the opportunity cost.

Each lithography step "adds value" to a product wafer based on the normal costs associated with that particular process step plus any profit that the company hopes to generate from the sale of the product. Determining these costs is a difficult task and requires the use of a traditional cost of ownership model. However, this exercise is a standard part of fab accounting and numbers for the value of a wafer at each step in the manufacturing process are usually available. Thus, the lithographer can often determine the value added at a particular step in the process by simply looking up the value of the wafer before and after that step. In this way, the opportunity cost associated with running a test wafer can easily be obtained using existing information.

A key point to note here is that most of the complications of the traditional cost of ownership approach are hidden in the opportunity cost. As mentioned above, lithographers often have access to the some of the outputs of the traditional cost of ownership models (the value of a product wafer at each step of the process), even though they usually have little access to the inputs. These outputs are of critical importance to the OCM and best yet, are readily available for use.

C. Extra Processing Costs

In comparing test wafers to product wafers, the extra costs incurred by manufacturers in running test wafers include:

1) the actual test wafer substrates themselves,
2) additional or nonstandard processing steps (e.g., using a top layer ARC),
3) the metrology (e.g., microscope inspections, SEM analyses, etc.) performed on these wafers that is not normally performed on product wafers, and
4) extra engineering time spent designing and analyzing an experiment or test and the resultant data.

Determining the costs of each of these items may or may not be an easy matter. Wafer costs are easily determined, even for partially processed wafers. At the very least, one could estimate the cost of a particular wafer structure as the cost of purchasing this wafer from a foundry. If the completed test wafer can be reclaimed, the value of the wafer to be reclaimed should be subtracted from the original cost of the substrate. The cost of additional processing steps could be difficult to ascertain. If the number of additional steps is small, the task should be manageable. Like wafer costs, if metrology costs within a company are not known, they can be estimated based on what an outside service would charge for the same work. Finally, engineering time should be added in (assuming the engineer could be occupied with other important tasks if not for this test wafer).

We have now addressed both the first and second variables in the equation for the OCM. Since the goal is to give an estimate of the cost of test wafers without the complexity of traditional cost of ownership models, the approach has been kept purposely simple and direct. As a result, reasonable estimates of the cost of test wafer processing can be made by lithographers (or engineers at any processing step, for that matter) with a minimum of effort.

IV. Comparison of Modeling and Test Wafer Processing

To those that regularly use lithography simulation, it is only natural to think that modeling can be used to help reduce the number of test wafers which must be processed in order to investigate, improve, or maintain a process. In fact, the reduction of the number of test wafers can be used as one of the many justifications for the use of modeling. Thus, let us consider a comparison between running test wafers and using a lithography model to obtain the same information. Consider the following example (typical numbers are assumed):

Experiment: To determine the merit of focus drilling, shoot eight focus-exposure matrices using 1 hour of stepper time and 4 hours of SEM time.

a) Opportunity Costs: Twenty product wafers were not processed, resulting in an opportunity cost of $1,000. (Note that some commodity products could have a lower opportunity cost, and high value items such as microprocessors could have a significantly higher opportunity cost.)
b) Extra Processing Costs: Eight 8" ultraflat wafers (at a cost of $150 each, minus a $50 reclaim value) plus 4 hours of SEM time (at $100/hour) equals $1,200.

TOTAL COST: $2,200.

Note that in the example above, extra engineering time for analyzing resultant data was not included.

There are several key points to note in the comparison of lithography simulation and test wafer processing. First, the cost of ownership for lithography simulation is essentially zero. Assuming a purchase price of $5,000 and thousands of simulations run during the lifetime of the model, the cost per simulated experiment is negligible (in the example above, nearly half the cost of this assumed model is recovered the first time it is used). Next, engineering time spent modeling is roughly equivalent to engineering time spent analyzing experimental results. Thus, this time need not be included in a cost comparison. Also, using modeling as opposed to running additional test wafers reduces overall waste and the risk of environmental insult. Finally, simulation produces highly accurate, repeatable, and reproducible results which are essential to high quality process characterization. Significantly more data can be (and usually is) collected with the model than can be justified when running test wafers.

V. Conclusions

The Opportunity Cost Model (OCM) developed by the authors is a new and simple solution to the problem of determining the cost of test wafer processing. Using existing techniques and available information, the OCM allows lithographers to become involved in the determination of how their functional area can increase or decrease their organization's profitability. The OCM represents situations in which both Accounting and Engineering are involved in key strategic decision making without the use of extensive new analysis or data gathering. Additionally, a tool such as the OCM can be used to cost justify the use of money-saving techniques such as lithographic modeling, increased in-line process monitoring, and process control strategies.

References

1. Ross Carnes and Mary Su, "Long Term Cost of Ownership: Beyond Purchase Price," *Proc., 1991 IEEE/SEMI Int'l. Semiconductor Manufacturing Science Symposium*, (1991) pp. 39-43.