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Benefits and Costs of Improved Measurements: The Case of Integrated-Circuit Photomask Linewidths

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ABSTRACT

Accurate dimensional measurements are vital to quality control in the semiconductor industry. This paper introduces an approach to estimating the dollar cost-savings from improving measurements of integrated-circuit photomask linewidths. The approach is illustrated with a case study of a hypothetical semiconductor device manufacturer who uses a Standard Reference Material (SRM) developed at the National Bureau of Standards to calibrate optical microscopes.

Benefits of investing in improved photomask linewidth measurements include reducing disputes between mask maker and mask customer, reducing waste of good photomasks, and increasing device yields. For the hypothetical manufacturer described in the study, these benefits were much greater than costs of implementing the new measurement procedures.

While the model is tailored to photomask linewidth measurements, many of its concepts can be applied to other types of measurements.

PREFACE

This research project was funded by the NBS Planning Office as part of its efforts to develop and demonstrate methods of evaluating economic impacts of NBS research. The topic chosen for study was NBS's research aimed at improving the measurement of linewidths on integrated-circuit photomasks used in the semiconductor industry.

This report is not intended to convey engineering information to those who make linewidth measurements in industry. For scientific and engineering information about linewidth measurements, see the publications by NBS scientists which are listed in appendix C to this report.

This study was based on published information, discussions with NBS scientists, and discussions with 12 integrated circuit manufacturers, four independent photomask producers, five measurement equipment and standards suppliers, six consultants, and one manufacturer of photolithography equipment. Most data for this study were collected during 1980.

The author is grateful for the information provided by individuals at various semiconductor industry firms. In addition, the author is indebted to John Jerke, Diana Nyyssonen, and Robert Scace of the National Bureau of Standards, Center for Electronics and Electrical Engineering who provided valuable insight into many aspects of linewidth measurements and helpful comments on the report draft. Thanks are due to Steve Weber, Harold Marshall, Greg Tassey, and Pat Donvito of NBS for their constructive criticism of the economic methodology used, and to Carroll Croarkin of the NBS Center for Applied Mathematics for her helpful comments. Credit is also due Mike Usle, now a graduate student at Brigham Young University, who conducted most of the research for the chapter concerning NBS research costs, and to Barbara Lippiatt, now a graduate student at American University, who conducted a search of the economics and technical literature.

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Purpose

The purpose of this report is to introduce a rigorous approach to estimating the cost savings from improved measurements of narrow lines on photomasks.[1] The approach uses a model which is based on many simplifying assumptions, listed in table 2.3 on page 20.

The Model

The simplified model predicts the cost savings per photomask for a hypothetical company which uses the Standard Reference Material SRM 474 and related measurement procedures. The National Bureau of Standards developed SRM 474 for calibrating optical microscopes which measure linewidths on integrated circuit (IC) photomasks.

Errors in mask measurements lead to the following problems: (1) mask waste if a good mask is rejected; (2) disputes if the mask buyer and mask seller disagree about whether the mask is within specifications; and (3) IC yield loss and related costs if a bad mask is accepted for use in IC production.[2]

The probabilities and costs associated with these problems are calculated for a single mask. Probabilities and costs are recalculated to reflect a reduction in measurement error resulting from a company calibrating its microscopes with the SRM 474 and adopting procedures recommended by NBS.

Results

The model is illustrated for a hypothetical company which produces photomasks and IC devices with approximately 3 micrometer-wide lines. For masks costing $1,000, the company would save $179 per mask by implementing NBS procedures in 1980. NBS is credited with $82 or about half of these savings. (It is assumed that companies would eventually improve measurements without NBS.) For masks costing $100 each, the company would save $15 per mask, of which NBS is credited with $7. Implementation costs are less than $2 per mask.

These results apply only for the values assumed for the hypothetical company. (These values are listed in table 3.1 on page 28.) A sensitivity analysis suggests that for other values (listed in figure 3.3 on page 44), actual benefits could be considerably higher or lower than the ones reported above. Benefits were strongly positive for most sets of values used in the sensitivity analysis.

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[1] The linewidths of interest are 0.5 to 10 micrometers wide. Photomasks are the patterned glass plates used in producing semiconductor integrated circuits (ICs).

[2] "Yield" is the percent of units which are not defective. Terms are defined in the glossary in appendix A.

Other effects

Several important benefits of the NBS research were not quantified for this report, although they are discussed qualitatively. These include improved measurement repeatability, improved measurement of linewidths on wafers, the design and production of IC devices with narrower lines, improved field reliability of IC devices, and improvements in the design and selection of linewidth measurement equipment.

Use of the method

The method described in this report can aid NBS planners or individual companies in understanding how improved measurements lead to cost savings. Economic analysis using models of this type may be useful to NBS when the industry involved is relatively homogeneous and good market data are available; and when considerable resources can be committed to the benefit-cost study, perhaps including participation by NBS scientists in the study.

Those using the model should be aware that it represents only the specific situation described by the assumptions on page 20. Many of these assumptions may require modification before applying the model to additional situations involving linewidth or other types of measurements.

1. INTRODUCTION

Purpose

The purpose of this report is to introduce a rigorous approach to estimating the cost savings from improved measurement of narrow lines (0.5 to 10 micrometers wide) on photomasks. Photomasks are the patterned glass plates used in producing semiconductor integrated circuits (ICs). The approach uses a model which is based on many simplifying assumptions, listed in table 2.3 on page 20.

Researchers in the NBS Semiconductor Technology Program have developed Standard Reference Materials (SRMs) and improved measurement methods for use in measuring linewidths on photomasks used in the semiconductor industry. This research is considered by NBS to be particularly successful.[1] An economic analysis appeared feasible because a list of possible users (people requesting information) was available.

Technical Background

This study is concerned with the measurement of narrow lines on photomasks, patterned glass plates used by the semiconductor industry in manufacturing integrated circuit (IC) devices. The IC manufacturing process can be compared to the printing of photographs, with the photomask acting as a transparency. The lines on the photomask -- so minute they can be seen only with a powerful microscope -- serve as patterns for producing ICs on silicon wafers. The wafers are later broken into tiny chips which are built into computers, instruments, automobiles, calculators, watches, and numerous other products.[2]

Linewidths on photomasks must be within specified dimensional tolerances for the mask to be acceptable to the IC manufacturer. Mask manufacturers can consistently ship masks within these tolerances only if they can make very accurate linewidth measurements. Generally these measurements are made using optical microscopes fitted with micrometer attachments of various types.

Consequences of erroneous measurements

The industry has encountered difficulties in making sufficiently accurate photomask measurements, leading to four costly consequences:

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[1] It was one of several semiconductor projects highlighted in the NBS 1978 Annual Report, and in 1980 two researchers involved received Commerce Department silver medals for their work. In budget size it is typical of NBS semiconductor research projects.

[2] For more information on ICs, see Scientific American, September 1977 issue; U.S. Department of Commerce, Industry and Trade Administration, A Report on the U.S. Semiconductor Industry (Washington, D.C.: U.S. Government Printing Office, 1979); and Robert I. Scace, Semiconductor Technology for the Non-Technologist, NBSIR 81-2197, (Washington, D.C.: National Bureau of Standards, 1981).

1. Bad masks are sometimes accepted for use in IC manufacturing. Using such masks to expose wafers results in incorrect line dimensions on the wafers.[1] Incorrect wafer line dimensions reduce IC yield, may reduce reliability of outgoing devices, and lead to other costs in IC manufacturing.[2] Devices which are outside of specifications must be scrapped or, at best, sold at a lower price for less demanding uses.

2. Good masks are sometimes rejected and scrapped, resulting in the cost of remaking those masks.

3. Measurement discrepancies have led to numerous and sometimes costly disputes between the mask manufacturer and the IC manufacturer concerning whether masks shipped are within specified dimensional tolerances.

4. Inaccurate linewidth measurements slow the move toward production of devices with smaller linewidths, thus deferring the benefits of these improved products.

Scope

In response to the problems described above, NBS began research in 1973 aimed at developing standards and procedures for accurate linewidth measurements on IC photomasks. This research has resulted in: (1) improved industry measurements of linewidths on photomasks using existing measurement equipment; (2) design changes in existing types of commercial linewidth measurement equipment and development of new types of measurement equipment; (3) improved selection of linewidth measurement equipment by mask houses and IC manufacturers; (4) improved adjustment and characterization of equipment for producing photomasks and IC devices; (5) measurement improvements in industries other than the semiconductor industry; and (6) scientific information useful in developing improved methods of measuring linewidths on wafers.[3]

Resources were not available to quantify all these benefits. Therefore, only the potential cost savings from improved photomask measurements using existing measurement equipment will be examined quantitatively in this report. The NBS outputs responsible for this result are the Standard Reference Materials (SRMs) 474 and 475 and related measurement procedures. These SRMs are used for calibrating optical microscopes to measure chromium-on-glass photomasks. The basic measurement pattern on the SRM 474 is shown in figure 1.1. The first SRM 474 was sold to an industrial user in May 1980.

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[1] For definitions of engineering and economics terms, see the glossary in appendix A.

[2] For example, personnel from one company stated that measurement discrepancies between their mask shop and IC production groups resulted in incorrect mask linewidths and IC yield problems. They believe that standardizing linewidth measurements between groups significantly improved yields for some IC products.

[3] These benefits were described by NBS scientists and industry personnel.

Figure 1.1 NBS Optical Microscope Linewidth Measurement Standard (SRM 474)

(A view of the basic measurement pattern)

Source: National Bureau of Standards, Standard Reference Material 474: Optical Microscope Linewidth Measurement Standard (document accompanying the SRM 474 artifact, June 9, 1980).

How NBS Results Reach Industry

The NBS linewidth measurement technology reaches industrial users through the paths described in figure 1.2.

A handful of companies supply linewidth-measurement systems (typically, optical microscopes fitted with a micrometer attachment). These companies transmit NBS technology to their customers through equipment design, instruction manuals, and personal contact. Some linewidth-measurement equipment manufacturers also sell calibration standards traceable to the SRM 474. In addition, there is at least one independent supplier of linewidth-measurement calibration standards traceable to the SRM 474.

The two basic sources of IC masks are independent producers and in-house mask shops in IC companies. These groups often provide standards, measurement procedures, and calibration services for their customers, thereby often transmitting NBS measurement technology.

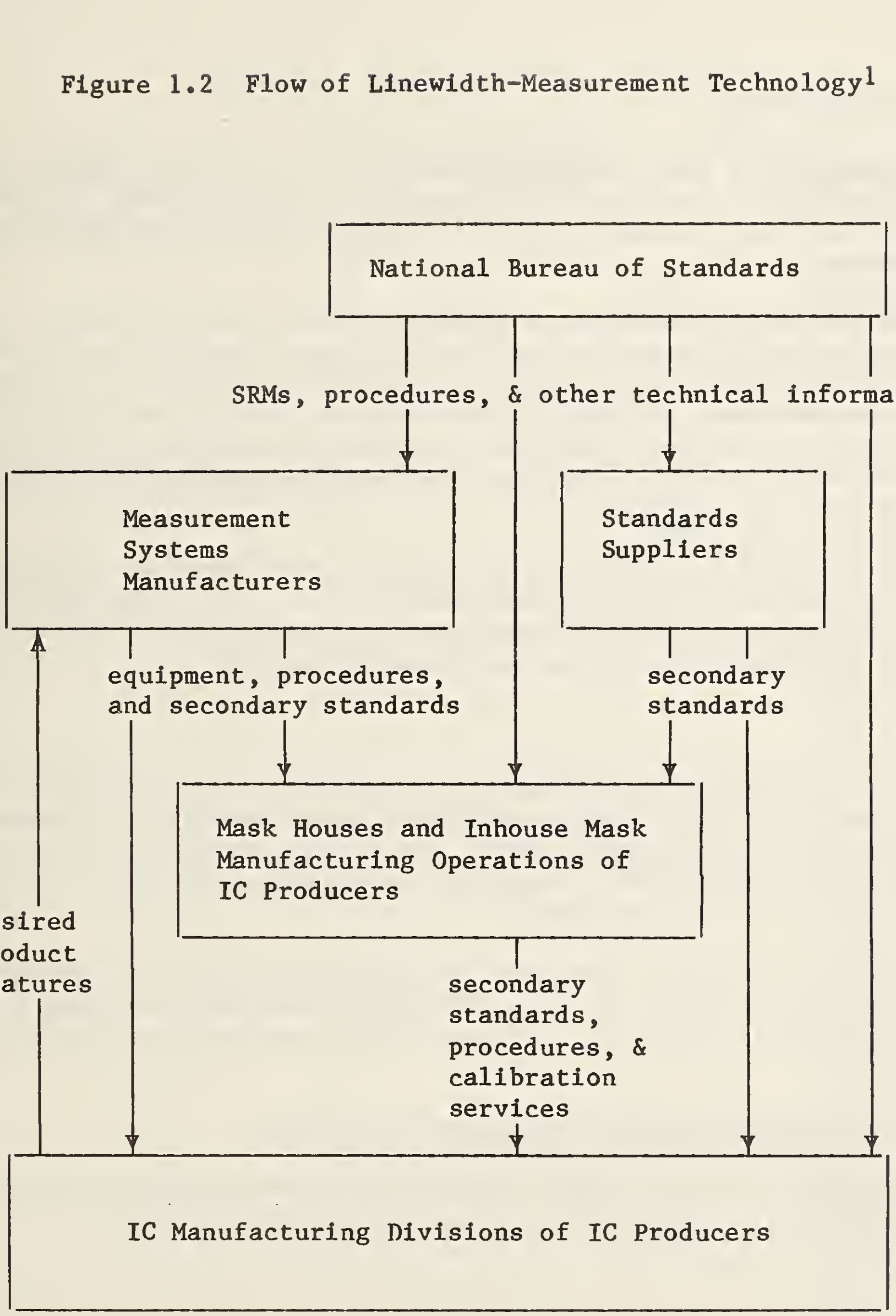
IC producers also obtain NBS photomask-measurement technology either directly from NBS or indirectly through other companies. In some cases they may transmit NBS technology to measurement equipment manufacturers by demanding features recommended by NBS.

The equipment manufacturers and standards suppliers appear to be the primary "leverage" points for disseminating NBS technology. By reaching the small number of companies in these groups, NBS can disseminate its technology to a large number of other organizations. Mask houses and inhouse mask shops are also leverage points for transmitting NBS technology.

In the future, standards-writing organizations (particularly, the American Society for Testing and Materials) will also transmit NBS linewidth measurement technology through publication of standards documents based on the NBS research.

The next two chapters examine the possible cost savings from using NBS linewidth measurement technology.

Figure 1.2 Flow of Linewidth-Measurement Technology[1]



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[1] In this figure, "standards" refers to photomask-like artifacts, not to standards documents. In the future, standards-writing organizations (particularly, the American Society for Testing and Materials) will also transmit NBS linewidth measurement technology through publication of standards documents based on the NBS research.

2. MASK ACCEPTANCE MODEL

This chapter describes a model for estimating the per-mask cost savings from adopting improved methods of measuring linewidths on photomasks. The model will be used in the next chapter to calculate cost savings for specified values of model parameters.

The model is based on the assumptions listed and discussed in table 2.3 on page 20. It was not feasible within the available resources to explore a variety of cases; thus, some assumptions were made to limit the scope of the analysis. Many assumptions were made to simplify the analysis and are not strictly true, although they may be good approximations for some situations. The assumptions were made based on the author's judgment following discussions with NBS scientists and industry personnel.

A major assumption used in this model is that the only error in measuring linewidths is a systematic bias in measurements; i.e., there are no random errors (measurements are perfectly consistent or repeatable).[1] However, the model could be modified to allow for random error as well.

Overview

The approach is to measure cost savings to the mask shop (or independent mask producer) and the IC producer from measurement improvements which reduce the frequency of buyer-seller disputes, reduce waste of good masks, and reduce use of "bad" masks in IC production. Improved measurements can reduce both the costs and frequency of these problems.

To find net benefits per mask, the cost of implementing improved measurement procedures is subtracted from the cost savings.[2] The equations used in the model are summarized in table 2.1. Terms in the equations are discussed later in this chapter.

2.1 COSTS OF MEASUREMENT-RELATED PROBLEMS (C1, C2, C3)

Erroneous measurements lead to three types of costs which can be quantified using this model. The first is C1, the cost of remaking a mask.

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[1] See the glossary in appendix A for definitions of measurement terms. For a discussion of measurement errors, see Ku, Harry, "Statistical Concepts in Metrology," in Handbook of Industrial Metrology, American Society of Tool and Manufacturing Engineers (New York: Prentice-Hall, 1967), pp. 20-50.

[2] Net benefits per mask are based on the number of masks which are good with respect to non-linewidth aspects (and may or may not be good with respect to linewidths). If the number of masks originally manufactured or the number shipped to customers were used instead, the per-mask benefits would be different.

Table 2.1 Summary of Equations[a]

Number	Equation	See Report Section	Definitions
(1)	$B = (C'-C'') \frac{UPW_{(t-s)}}{T} (SPW_s) - C4$	2.4	B = Total net benefits per mask with NBS B^* = Total net benefits per mask without NBS C' = Per-mask cost of measurement error (before)[a] C'' = Per-mask cost of measurement error (after)[a] $UPW_{(t-s)}$ = Uniform Present Worth discounting factor for time period "t-s" t = life of measurement procedures (number of years before obsolescence) as of base year (e.g. 1980) s = number of years after base year that the procedures are adopted at a particular company, with NBS ("t-s" is the number of years the procedures are useful at a particular company), s^* = number of years after base year that the procedures are adopted at a particular company, <u>without</u> NBS T = analysis period SPW_s = Single Present Worth discounting factor for time period "s" $C4$ = per-mask cost of implementing new procedures (with NBS) $C4^*$ = per-mask cost of implementing new procedures (without NBS)
(2)	$B^* = (C'-C'') \frac{UPW_{(t-s^*)}}{T} (SPW_s^*) - C4^*$	2.5	
(3)	$C' = C1'(P_2'+P_3'+P_5'+P_6') + C2'(P_2'+P_5') + C3'(P_4')$	2.1 and 2.2	$C1'$ = Mask remake cost (before) $C2'$ = Dispute cost (before) $C3'$ = Yield loss and related costs (before)

Table 2.1 Summary of Equations[a] (continued)

	Equation	Section	Definitions
(4)	$C'' = C1''(P_2''+P_3''+P_5''+P_6'') + C2''(P_2''+P_5'') + C3''(P_4'')$	2.1 and 2.2	P_2' = Probability of good mask rejected by IC mfr., with dispute (before)[b]
			P_3' = Prob. of good mask rejected by mask shop (before)[b]
			P_4' = Prob. of bad mask accepted (before)[b]
			P_5' = Prob. of bad mask accepted by mask shop/ rej. by IC mfr./dispute (before)[b]
			P_6' = Prob. of bad mask rejected (before)[b]
			C1" through C3" and P2" through P6"[b] have similar definitions for <u>after</u> improving measurements
(5)	$P_i' = \int_{A1_i'}^{A2_i'} f(x)dx$	2.2	P_i' = Probabilities of paths described in figure 2.1 (before)
			$f(x)$ = Probability density function of a mask with respect to linewidths
(6)	$P_i'' = \int_{A1_i''}^{A2_i''} f(x)dx$	2.2	$A1_i'$ and $A2_i'$ = Lower and upper limits of range in which a mask linewidth must be for path "i" in figure 2.1 to occur (before)
			P_i'', $A1_i''$ and $A2_i''$ have similar definitions for after improving measurements
(7)	$C4 = \frac{2}{kT}\{ C5 + C6\ UPW_{(t-s)} + \sum_{i=1}^{j} C7_i\ SPW_{u(i)} \} SPW_s$	2.3	k = Number of masks measured annually at one company (kT is the total number measured over the analysis period)
			C5 = Initial cost of improving measurements
			C6 = Equal annual costs of improving measurements

Table 2.1 Summary of Equations[a] (continued)

	Equation	Section	Definitions	
(8)	$C4^* = \frac{2}{kT} \{ C5 + C6\ UPW_{(t-s^*)} + \sum_{i=1}^{j} C7^*_i\ SPW_{u(i)^*} \}\ SPW^*_s$	2.5	j	= Number of "other" cost items
			$C7_i$	= Other costs of improving measurements
			$u(i)$	= Number of years before cost item $C7^*_i$ occurs
			$u(i)^*$	= Number of years before cost item $C7^*_i$ occurs. If $u(i)^* = s$ then $C7^*_i = 0$.
(9)	$\Delta B = B - B^*$	2.5	ΔB	= Benefits credited to NBS research
			B^*	= Benefits per mask that would occur even without NBS research

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[a] Variables with a prime (') are before adopting improved measurement procedures; variables with a double prime (") are after adopting improved procedures. Variables with an asterisk * are for the hypothetical situation in which NBS did not conduct its measurement research.

[b] See figure 2.1.

The second, C2, is the cost of resolving measurement disagreements between the IC manufacturer and the mask shop. Costs of resolving disputes may include remeasurement by both parties at their respective sites, travel to the other site to remeasure masks, and management time.

The third, C3, is the cost if a bad mask is used in IC production. This is the most difficult cost to estimate. The average cost of using a bad mask is used rather than the catastrophic cost that might occasionally occur.

There are at least four sources of cost C3: (1) loss of IC device yield. The full value of the rejected devices may be lost, or substandard devices may be sold for less demanding applications at a lower price; (2) the cost of identifying the source of IC yield loss and correcting the problem. If the cause is not correctly traced, much engineering time may be lost trying to improve yields by adjusting other aspects of the manufacturing process; (3) there may be costs associated with field failure of IC devices with incorrect linewidths[1]; and (4) if IC yield losses are traced to the bad mask, then the mask itself will need to be replaced.[2]

Improved measurements may reduce the costs, C2 and C3, that result if a measurement-related problem occurs. As the next section describes, improved measurements may also reduce the probabilities that C1, C2, and C3 will occur.

2.2 PROBABILITIES OF MEASUREMENT-RELATED PROBLEMS (P_2 THROUGH P_6)

This section explains how to estimate the probabilities P_2 through P_6 that measurement-related problems will occur.

Decision tree

Figure 2.1 shows the different possible events involving mask production and measurement. For example, consider the path marked by the heavy line in figure 2.1. First (column A), a mask is manufactured which is good with respect to all non-linewidth characteristics. It may or may not be good with respect to linewidths. For the path marked by the heavy line, the mask is assumed to be good with respect to linewidths (column B). That is, its use will not lead to yield losses due to faulty mask line dimensions. (For certain other paths in figure 2.1, the mask is bad with respect to linewidths.) The entry in column B shows whether a mask is actually good or bad. Entries in later columns show whether the mask is thought to be good or bad as a result of measurements.

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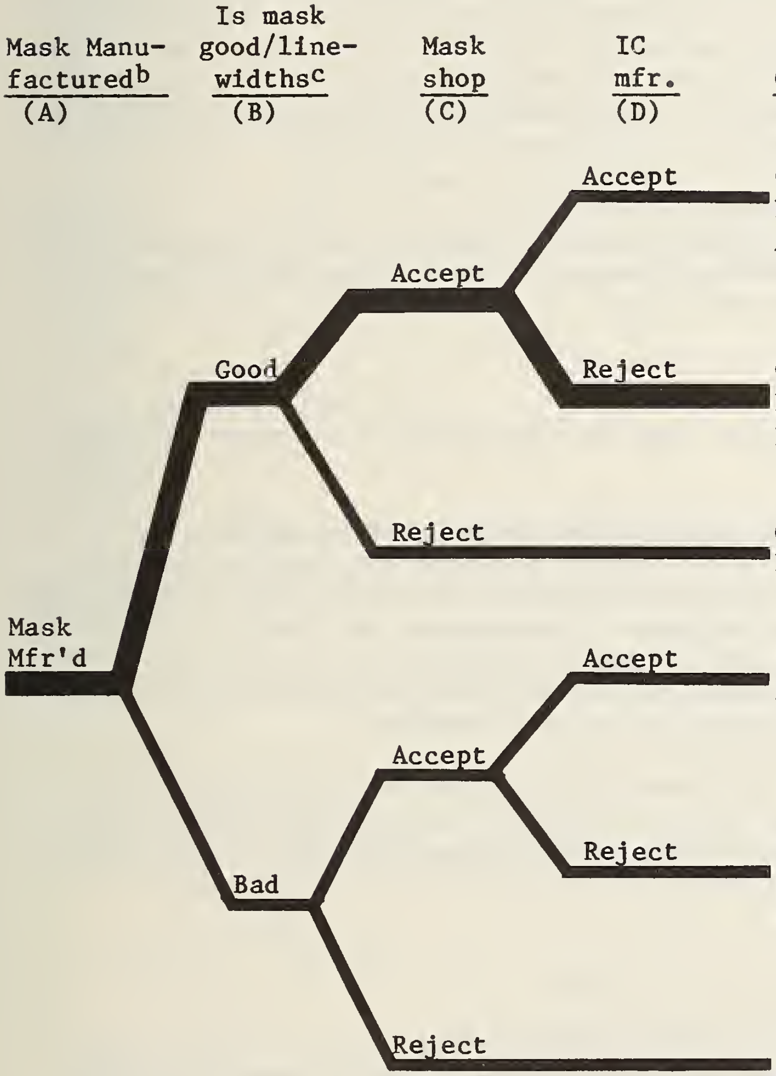
[1] Many companies responding to a survey conducted by Charles River Associates for the National Bureau of Standards reported that better linewidth measurements led to improved product reliability (in addition to reducing yield loss). Charles River Associates, Productivity Impacts of NBS R&D: A Case Study of the Semiconductor Technology Program, Summary Volume, June 1981.

[2] Replacing a bad mask creates a cost, although presumably it is less costly than the alternative of continuing to use the bad mask.

Figure 2.1 Possible Outcomes of Mask Acceptance Measurements[a]



Outcome	Probability	Cost of outcome
Good Mask Accepted	P_1' or P_1''	No cost[d]
Good Mask Rejected, Dispute	P_2' or P_2''	Mask remake--C1' or C1" Dispute--C2' or C2"
Good Mask Rejected	P_3' or P_3''	Mask remake--C1' or C1"
Bad Mask Accepted	P_4' or P_4''	Yield loss and related costs--C3' or C3"
Dispute, Bad Mask Rejected	P_5' or P_5''	Dispute cost--C2' or C2" Mask remake--C1' or C1"
Bad Mask Rejected	P_6' or P_6''	Mask remake--C1' or C1"

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[a] Prime (') refers to before adopting improved measurements; probabilities and costs must be recalculated after adopting improved measurements (").

[b] Mask is assumed to be good with respect to defects, registration, and other non-linewidth specifications.

[c] Is mask good with respect to linewidth specifications?

[d] Cost of path 1 is the baseline for measuring other costs and so equals zero.

Continuing to follow the path marked by the heavy line in figure 2.1, the mask is measured by the mask shop and found to be acceptable for shipment to the IC manufacturer (column C). At the IC manufacturer, the mask is erroneously measured as being outside specifications and is rejected (column D). The returned mask is remeasured by both the mask manufacturer and the IC manufacturer, and rejected again by the IC manufacturer. This path occurs with a probability P_2 for a single mask.

The last column in figure 2.1 shows the costs that arise if path "i" occurs. For example, with the path "good/accept/reject" (path 2), a dispute occurs with cost C2 and the mask must be remade at cost C1.[1] Thus, the cost of the "good/accept/reject path" is C1 + C2.[2]

Calculating path probabilities

The path probabilities P_2 through P_6 must be determined in order to find the cost of measurement error.[3]

Often, the probabilities of paths in decision trees are determined by calculating the probabilities of each step in the path and then multiplying along the path. However, in this case, calculating probabilities of each step would be complicated. A simpler approach is used here. It involves identifying the range of actual mask linewidths for which all steps in a path can occur, and then figuring out the likelihood that a mask will have linewidths in this range, based on knowledge of the mask production process.

For example, to calculate P_2, first we must determine the range of mask linewidths (from $A1_2$ to $A2_2$) for which a mask will be good, accepted by the mask manufacturer, and rejected by the IC manufacturer. Methods for determining the limits $A1_i$ and $A2_i$ for each path in figure 2.1 are described in appendix 2B to this chapter.

Probability of linewidths between $A1_i$ and $A2_i$

To determine the probability that mask linewidths will be in the range $A1_i$ to $A2_i$, we must estimate (or assume) the distribution of actual mask linewidths, after eliminating masks which have non-linewidth defects. By normalizing the

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[1] We assume disputes are won by the IC manufacturer. See the assumptions in table 2.3.

[2] The baseline against which costs of various outcomes are determined is the situation in which a good mask is accepted (path 1). By definition, the costs of path 1 are zero.

[3] A path probability is the probability that the sequences of events described by the path will occur.

curve so that the area under the curve equals one, the curve is converted to a probability density function.[1] Figure 2.2 shows two possible probability density functions which reflect the distribution of masks with respect to actual linewidths.

The reader should keep two points in mind: (1) these curves are based on the distribution of actual linewidths, not the distribution of measurements; and (2) they are based on the distribution of linewidths among masks, not within a single mask. (Linewidths are assumed to be uniform within a mask.)[2]

The probability that a mask will have linewidths between $A1_i$ and $A2_i$ (i.e., the probability of path "i") is the area under the curve between $A1_i$ and $A2_i$, as shown in appendix 2A-figure 2.3. The mathematical expression for this is:

$$P_i = \int_{A1_i}^{A2_i} f(x)\, dx. \qquad (10)$$

where:

P_i = the probability of a path described in figure 2.1,

$A1_i$ and $A2_i$ = lower and upper limits of range in which mask linewidths must lie for path "i" in figure 2.1 to occur, and

$f(x)$ = probability density function of a mask with respect to linewidths.

By varying "i" from two to six, the formula gives probabilities P_2 through P_6. (It is not necessary to compute the zero-cost path probability, P_1.)

For example, the probability of good/accept/reject, P_2, is given by the formula:

$$P_2 = \int_{A1_2}^{A2_2} f(x)\, dx. \qquad (11)$$

The area P_2 is shown in figure 2.3. The curve in figure 2.3 is drawn for the situation where the IC producer's bias, N, is greater than the mask shop's bias, M, and both M and N are positive.

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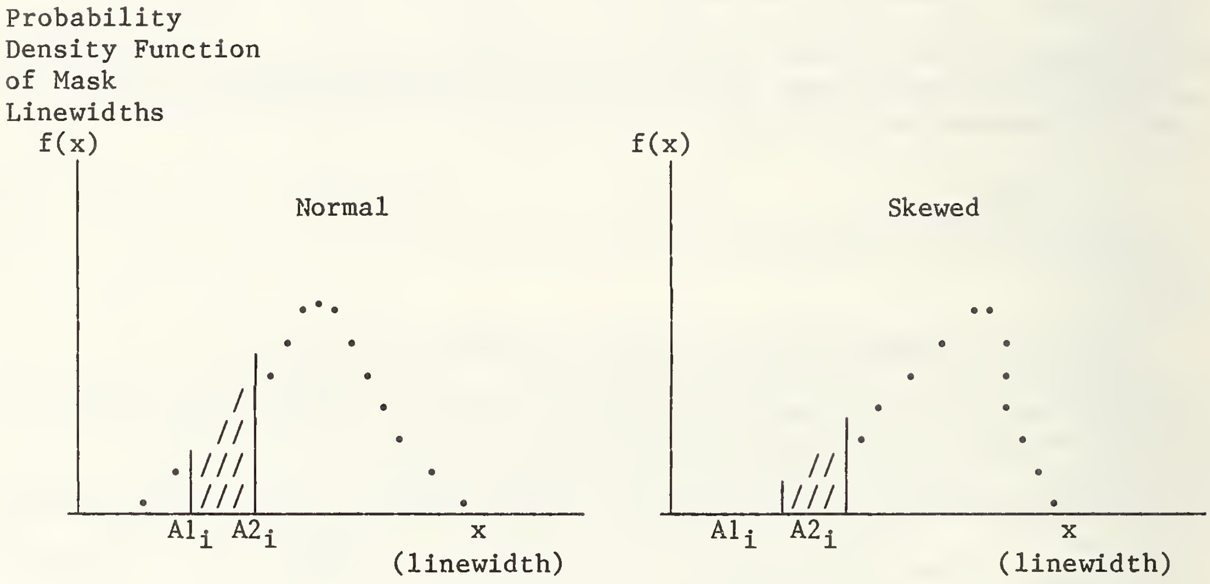
[1] For an explanation of the concept of probability density functions, refer to any good statistics textbook, such as Mills, Frederick C., Statistical Methods (New York: Holt, Rinehart and Winston, various editions).

[2] See table 2.3 with assumptions.

Figure 2.2

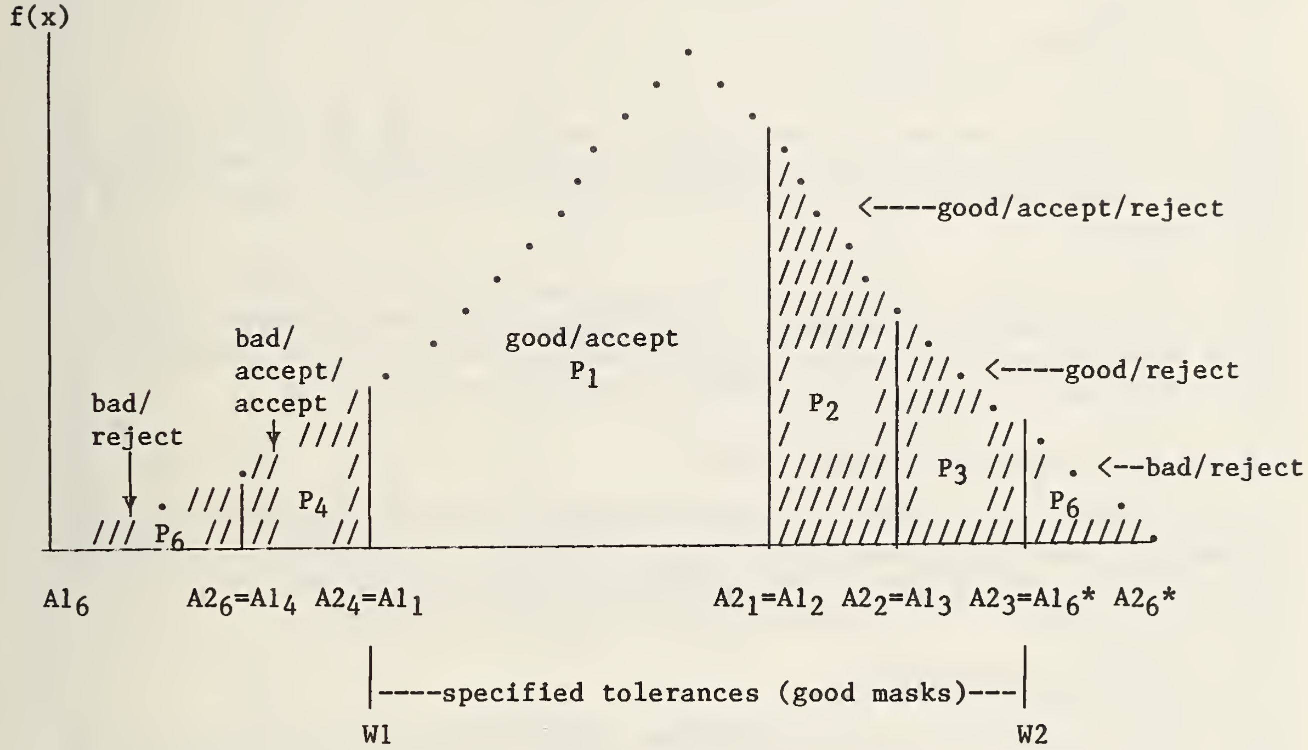
Two Possible Distributions of Masks with Respect to Line Dimensions[a]



|///| probability a mask will have line dimensions between $A1_i$ and $A2_i$

[a] f(x) is based on the distribution of <u>actual</u> linewidths <u>among</u> masks, not measured linewidths or linewidths on a single mask.

Figure 2.3 Path Probabilities where $N>M>0$[a]



P_5 (bad/accept/reject) = 0

f(x) = probability density function for a mask with respect to linewidths

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[a] This example assumes that the IC producer's measurement bias, N, is greater than the mask shop's measurement bias, M, and that both are positive.

In this example, P_6 is represented by two separate areas, so that the formula is:

$$P_6 = \int_{A1_6}^{A2_6} f(x)dx + \int_{A1^*_6}^{A2^*_6} f(x)dx. \qquad (12)$$

Table 2.2 gives formulas for computing $A1_i$ and $A2_i$, given the measurement biases of the mask shop and IC producer, and the distribution of mask linewidths. The method for computing these limits is explained in appendix 2B to this chapter.

Improving measurement methods affects the probabilities P_1 through P_6 and involves a movement between paths. For example, with better measurements there would be more good masks accepted (an increase in P_1) and fewer good masks rejected by the IC manufacturer (a decrease in P_2).

Computing Costs of Measurement Errors

To find "before" and "after" costs of measurement error,[1] the values for P_2' through P_6' and P_2'' through P_6'' and the values for C1' through C3' and C1" through C3" are substituted into equations (3) and (4) in table 2.1. Other terms in equation 1 are discussed in the following sections.

2.3 IMPLEMENTATION COSTS (C4)

The costs of implementing new measurement procedures are found by adding up costs that have been discounted to their present values, according to equation 7 in table 2.1.

The factor "two" is used in equation 7 because the new procedures must be implemented by both the mask shop and IC producer, doubling the cost. It is divided by "k" (the number of masks measured per year) and "T" (the number of years in the analysis period) to put costs on a per-mask basis.

Equal annual future costs are discounted to their present value using a Uniform Present Worth (UPW) discounting factor. One-time future costs are discounted using Single Present Worth (SPW) factors. Discounting is discussed in appendix B. Individual cost items are discussed below.

Startup costs (C5)

Management time is needed to become familiar with improved procedures, to determine what changes are needed to adopt them, and to coordinate implementation, including conducting any needed training sessions. Training costs for operators, technicians and engineers are estimated using number of hours and costs per hour.

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[1] C' and C" in equation 1 of table 2.2.

Table 2.2 Formulas for Limits of Integration in Calculating Path Probabilities[a]

Path probabilities P_i are calculated using the formula $P_i = \int_{A1_i}^{A2_i} f(x)dx$ where $A1_i$ and $A2_i$ have the following values:

Conditions:		M>N>0		M<N<0		N>M>0		N<M<0		M>0 and N<0		M<0 and N>0	
Limits of integration:		$A1_i$	$A2_i$	$A1_i$	$A2_i$	$A1_i$	$A2_i$	$A1_i$	$A2_i$	$A1_i$	$A2_i$	$A1_i$	$A2_i$
P_2-Good/ accept/ reject	$W1 \le x \le W2$ $W1-M \le x \le W2-M$ $x<W1-N$ or $x>W2-N$	$A1_2=A2_2$ P2=0		$A1_2=A2_2$ P2=0		W2-N	W2-M	W1-M	W1-N	W1	W1-N	W2-N	W2
P_3-Good/ reject	$W1 \le x \le W2$ $x<W1-M$ or $x>W2-M$	W2-M	W2	W1	W1-M	W2-M	W2	W1	W1-M	W2-M	W2	W1	W1-M
P_4-Bad/ accept/ accept	$x<W1$ or $x>W2$ $W1-M \le x \le W2-M$ $W1-N \le x \le W2-N$	W1-N	W1	W2	W2-N	W1-M	W1	W2	W2-M	$A1_4=A2_4$ P4=0		$A1_4=A2_4$ P4=0	
P_5-Bad/ accept/ reject	$x<W1$ or $x>W2$ $W1-M \le x \le W2-M$ $x<W1-N$ or $x>W2-N$	W1-M	W1-N	W2-N	W2-M	$A1_5=A2_5$ P5=0		$A1_5=A2_5$ P5=0		W1-M	W1	W2	W2-M
P_6/Bad/ reject	$x<W1$ or $x>W2$ $x<W1-M$ or $x>W2-M$	$A1_6=0$ $A1_6^*=W2$	$A2_6=W1-M$ $A2_6^*=\infty$	$A1_6=0$ $A1_6^*=W2-M$	$A2_6=W1$ $A2_6^*=\infty$	$A1_6=0$ $A1_6^*=W2$	$A2_6=W1-M$ $A2_6^*=\infty$	$A1_6=0$ $A1_6^*=W2-M$	$A2_6=W1$ $A2_6^*=\infty$	$A1_6=0$ $A1_6^*=W2$	$A2_6=W1-M$ $A2_6^*=\infty$	$A1_6=0$ $A1_6^*=W2-M$	$A2_6=W1$ $A2_6^*=\infty$

---

[a] W1 and W2 are the lower and upper bound linewidth specs; M and N are the mask shop and IC manufacturer measurement biases. Other symbols are defined in table 2.1. These formulas assume that $|N-M \le W2-W1$, $|N| \le W2-W1$, and $|M| \le W2-W1$. $A1_i$ and $A2_i$ are determined by the condition $A1_i \le x \le A2_i$ and by the restrictions on x in the first column above.

Improving measurement procedures may involve acquiring new measurement systems or retrofitting existing systems. Time spent selecting equipment should be included here if it was not included under management time. The cost of buying, or manufacturing and measuring, calibration standards is also included. If standards must be replaced during the analysis period "T," the replacement cost is included.

If the calibration process uses a computer program, its development time is included as a startup cost. The cost of using the program is included under ongoing costs, discussed below.

Time needed to adjust and calibrate measurement systems--in excess of what was needed under the old procedures--is included.

Ongoing costs (C6 and C7)

The cost of any additional time needed to periodically check, adjust, and calibrate equipment is included. Any increase or decrease in the time to make routine measurements is also included.

2.4 DISCOUNTING AND TIME-RELATED VARIABLES (UPW, SPW, r, t, T, s)

Two discounting factors are used in the net benefits equation (1) in table 2.1 to adjust for the time value of money.

The factor $UPW_{(t-s)}/T$ is a Uniform Present Worth factor divided by the analysis period, T. It adjusts for the fact that benefits occur over a period of time and puts them on a per-mask basis. This is explained further in appendix B. The Single Present Worth factor SPW_s adjusts for the fact that improved measurement procedures are implemented in a future year.

"r" is the real discount rate, used in selecting UPW and SPW factors. "s" is the number of years after the base year (e.g., 1980) that the procedures are implemented. It is also used in selecting UPW and SPW factors. "t" is the assumed life of the measurement procedures at the company being analyzed. It is used in selecting UPW factors.

Discounting is discussed further in appendix B.

2.5 EFFECTS IF NBS HAD NOT DONE RESEARCH (B*, C4*)

The costs savings in equation (1) and the costs in equation (7) in table 2.1 were calculated assuming that, without the NBS technology, firms would have made no progress toward improving linewidth measurements. However, this is unrealistic. Even without NBS, firms will improve their measurement methods. Therefore, to avoid exaggerating the value of NBS's contribution, we need to compare what does happen with what probably would have happened if NBS had not conducted its research.

It seems likely that NBS work affected both the nature and timing of linewidth measurement advances. However, to simplify the analysis, this model considers only NBS's effect on timing of advances.[1]

The values used in calculating net benefits reflect the situation that would prevail if NBS had not conducted its research. This model assumes that, without NBS, companies would adopt measurement improvements later so that "s" is changed to "s*." We also assume that costs of implementing measurement improvements are essentially the same except that they are incurred later. Finally, we assume that the technology becomes obsolete in a certain year regardless of whether it is from NBS or another source, so that the value for "t" does not change.

The net cost savings, B-B*, are the cost savings with NBS less the cost savings that would have been realized even without NBS. Both types of cost savings are averaged over the number of masks produced during the analysis period, T.

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[1] This approach was used by Marshall and Ruegg in estimating benefits of NBS efforts to develop a new type of roofing shingle. Marshall, Harold and Ruegg, Rosalie, Efficient Allocation of Research Funds: Economic Evaluation Methods with Case Studies in Building Technology, National Bureau of Standards Special Publication 558 (Washington, D.C.: U.S. Government Printing Office, 1979), p. 20.

APPENDIX 2A: ASSUMPTIONS

Table 2.3 Assumptions

Assumption	Discussion
There is an unknown measurement difference between mask buyer and mask supplier.	Many suppliers try to keep track of measurement discrepancies with customers and adjust mask dimensions accordingly. But even for these companies, measurement discrepancies with customers are probably unknown at least some of the time. If untrue, the assumption may overstate benefits of improved measurements.
Mask design and specifications are not changed as a result of improved measurements.	Actually, improved ability to measure frequently leads to a further shrinking of circuits, resulting in higher performance and/or lower cost devices. If untrue, this assumption may significantly understate economic benefits of improved measurements.
The specifications state that all lines must fall between certain limits. Masks measured as being outside these specs are rejected by whoever is doing the measuring; masks measured as being inside are accepted.	In fact, the mask shop may give the benefit of the doubt to the IC manufacturer on marginal masks (or vice versa). Also, the mask shop may purposely build in a margin for error by rejecting masks barely within the specifications. Finally, it is possible that people sometimes bias their measurements so as to get the "right" number.
Masks measured are used in IC production.	A small percentage of masks are used to make other masks, so are not used directly in IC production.
Any delays in mask delivery due to measurement error do not increase costs.	The startup of a new wafer fabrication process might conceivably be delayed if a needed mask is not available on time. This assumption may sometimes understate the benefits from improved measurements.
The measurement differences between mask buyer and mask supplier are stable.	Many measurement systems "drift" from day to day so that the difference from other firms will change over time.

Table 2.3 Assumptions (continued)

Assumption	Discussion
There is no random error. Measurements are perfectly repeatable. (The standard deviation σ of the measurement distribution is zero.)	Some spread of measurements within an organization is likely, and this spread may be significant. This assumption probably understates the benefits of improved measurement procedures, since NBS methods are designed to reduce random error.
Measurement bias is the same for all mask shop measurement systems.	The bias typically varies between production and quality control groups in the mask shop, whether they are using similar or different measurement systems.
Any deviation of actual linewidths from specifications is uniform across the mask.	The amount of deviation of actual dimensions from specified dimensions actually may vary across a mask. The within-mask variation in this deviation may be significant at some linewidths, but is thought to be insignificant at the linewidth target values (3 micrometers) used in chapter 3 in applying the present model.
Masks cause yield losses if and only if linewidths are outside specified tolerances. Masks inside this range never cause yield losses due to line dimensions.	Actually, some masks outside of specifications may be completely adequate for IC production, and some masks within specifications may lead to yield losses, depending on other factors in the IC manufacturing process.
Disputes are always won by the IC manufacturer.	More likely, disputes are sometimes won by one party and sometimes by another.
Lines measured are of one polarity (all clear or all opaque).	Masks always have both clear and opaque lines, but for some devices dimensions may be critical only for clear, or only for opaque, lines.
Mask inspection and measurement for features other than line dimensions is 100 percent accurate.	Actually, some error is likely to exist in non-linewidth-related aspects of inspection and measurement.
No masks are rejected for non-linewidth defects by the IC producer.	Actually, some masks will be rejected for other reasons, such as pinholes or ragged line edges.

Table 2.3 Assumptions (continued)

Assumption	Discussion
There are no costs to shipping masks.	The fact that such costs exist introduces a very minor error into the model.
If NBS had not conducted its research, companies would have obtained the same measurement technology later from other sources.	Most likely, measurement technology acquired from sources other than NBS would be different in nature as well as in timing from NBS technology.
Costs of implementing the hypothetical non-NBS technology would be the same, but incurred later, as costs for implementing NBS technology.	This is likely to be true only if the two types of technology are the same (see preceding assumption).
NBS and non-NBS technology would become obsolete in the same year.	This is likely to be true only if the two types of technology are the same (see preceding assumptions).

APPENDIX 2B: DETERMINING $A1_i$ AND $A2_i$

This appendix explains how the limits $A1_i$ and $A2_i$ are selected for calculating the probabilities of the paths described in section 2.2. The reader will recall that P_i is the probability that all conditions describing path "i" in figure 2.4 will hold, i.e., it is the probability the mask will have line dimensions between $A1_i$ and $A2_i$ where $A1_i$ and $A2_i$ are determined by the particular path being studied. P_i is calculated from the expression

$$P_i = \int_{A1_i}^{A2_i} f(x)dx, \tag{13}$$

where f(x) is the probability density function of masks with respect to line dimensions. (Examples of f(x) are shown in figure 2.2.)

To find the limits $A1_i$ and $A2_i$, first we determine the conditions for each step in a path shown in figure 2.4 (similar to figure 2.1) to take place. For example, consider path 2, marked by the heavy line in figure 2.4.

Example for path 2

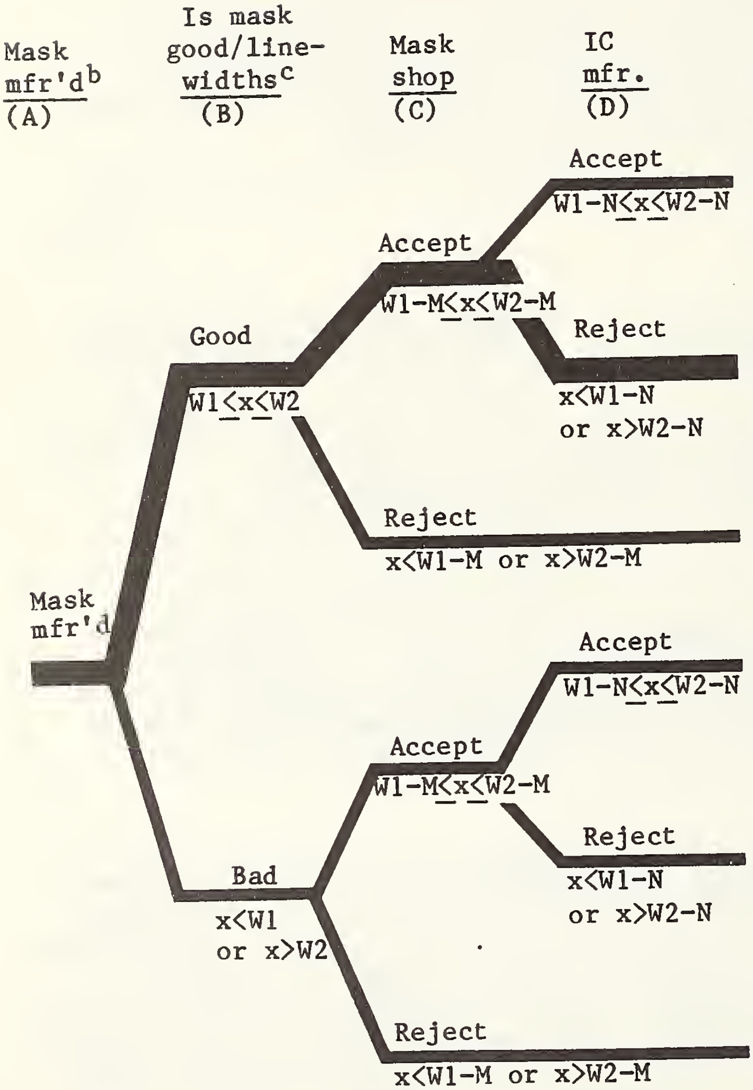
Column B: Conditions for mask to be "good." Let "x" be the actual mask linewidth, assumed to be the same for all lines on a mask. By assumption, masks are good only if their lines are within specified dimensional tolerances W1 and W2. Thus, a mask will be good if $W1 \leq x \leq W2$ and the mask will be bad if $x<W1$ or $x>W2$. For path 2, the mask is good so that $W1 \leq x \leq W2$ is written in column B in figure 2.4.

Column C: Conditions for acceptance by the mask shop. Let "y" be the line dimension as measured by the mask shop. This model assumes that the mask shop will accept masks for shipment to its customers if and only if the linewidths are measured as being within specifications. Thus, the mask is accepted by the mask shop if $W1 \leq y \leq W2$. The mask is rejected if $y<W1$ or $y>W2$. But since $y = x + M$, where M is the mask shop's measurement bias, the acceptance condition can be rewritten: $W1 \leq x+M \leq W2$, or $W1-M \leq x \leq W2-M$. The mask will be rejected if $x<W1-M$ or $x>W2-M$. For path 2, the mask is accepted by the mask shop, so that $W1-M \leq x \leq W2-M$ is written in column C.

Column D: Conditions for rejection by the IC manufacturer. Where "z" is the value measured by the IC manufacturer, a mask is accepted by the IC manufacturer if $W1 \leq z \leq W2$, and it is rejected if $z<W1$ or $z>W2$. Since $z=y+N$, the IC manufacturer will accept the mask if $W1-N \leq x \leq W2-N$, where N is the IC manufacturer's measurement bias. The mask will be rejected if $x<W1-N$ or $x>W2-N$. For path 2, the mask is rejected so that $x<W1-N$ or $x>W2-N$.

These conditions are written for path 2 in the appropriate columns in figure 2.4. All the conditions on path 2 must hold for the complete path to occur with probability P_2. Similar restrictions are also written for paths 3, 4, 5, and 6.

Figure 2.4 Conditions for Various Paths[a]



Outcome	Path probability	Cost of outcome
Good Mask Accepted	P_1' or P_1''	No cost[d]
Good Mask Rejected, Dispute	P_2' or P_2''	Mask Remake--C1' or C1" Dispute--C2' or C2"
Good Mask Rejected	P_3' or P_3''	Mask Remake--C1' or C1"
Bad Mask Accepted	P_4' or P_4''	Yield Loss and related costs--C3' or C3"
Dispute, Bad Mask Rejected	P_5' or P_5''	Dispute Cost--C2' or C2" Mask remake--C1' or C1"
Bad Mask Rejected	P_6' or P_6''	Mask remake--C1' or C1"

---

[a] Prime (') refers to before adopting improved measurements; probabilities and costs must be recalculated after adopting improved measurements, represented by a double prime (").

[b] Mask is assumed to be good with respect to defects, registration, and other non-linewidth specifications.

[c] Is mask good with respect to linewidth specifications?

[d] Cost of path 1 is the baseline for measuring other costs and so equals zero.

Next we determine the limits $A1_2$ and $A2_2$ which are consistent with all the restrictions on x shown in figure 2.4. Continuing with the example of path 2, we ask: For what range of line dimensions will masks be good masks (column B), accepted by the mask shop (column C), and rejected by the IC manufacturer (column D)? I.e., for what $A1_2$ and $A2_2$ do the following hold:

mask is between $A1_2$ and $A2_2$, i.e.... $A1_2 \leq x \leq A2_2$

mask is good, i.e................... $W1 \leq x \leq W2$

accepted by mask shop, i.e.......... $W1-M \leq x \leq W2-M$, and

rejected by IC manufacturer, i.e.... $W2-N < x$ or $x < W1-N$.

One method of finding the limits $A1_i$ and $A2_i$ is to draw a graph showing the relative positions of the values W1-N, W1-M, W1, W2, W2-N and W2-M, and to find by inspection the range $A1_i$--$A2_i$ which satisfies the conditions listed above. For example, if the IC producer's measurement bias (N) is greater than the mask shop's bias and both are positive ($N>M>0$), the relative locations of W1-M, W1-N, etc., are as shown in figure 2.5.

The limits $A1_i$ and $A2_i$ used in calculating probabilities P_i are shown in figure 2.5. For example, for path 2 (good/accept/reject), the restrictions

$W1 \leq x \leq W2$,

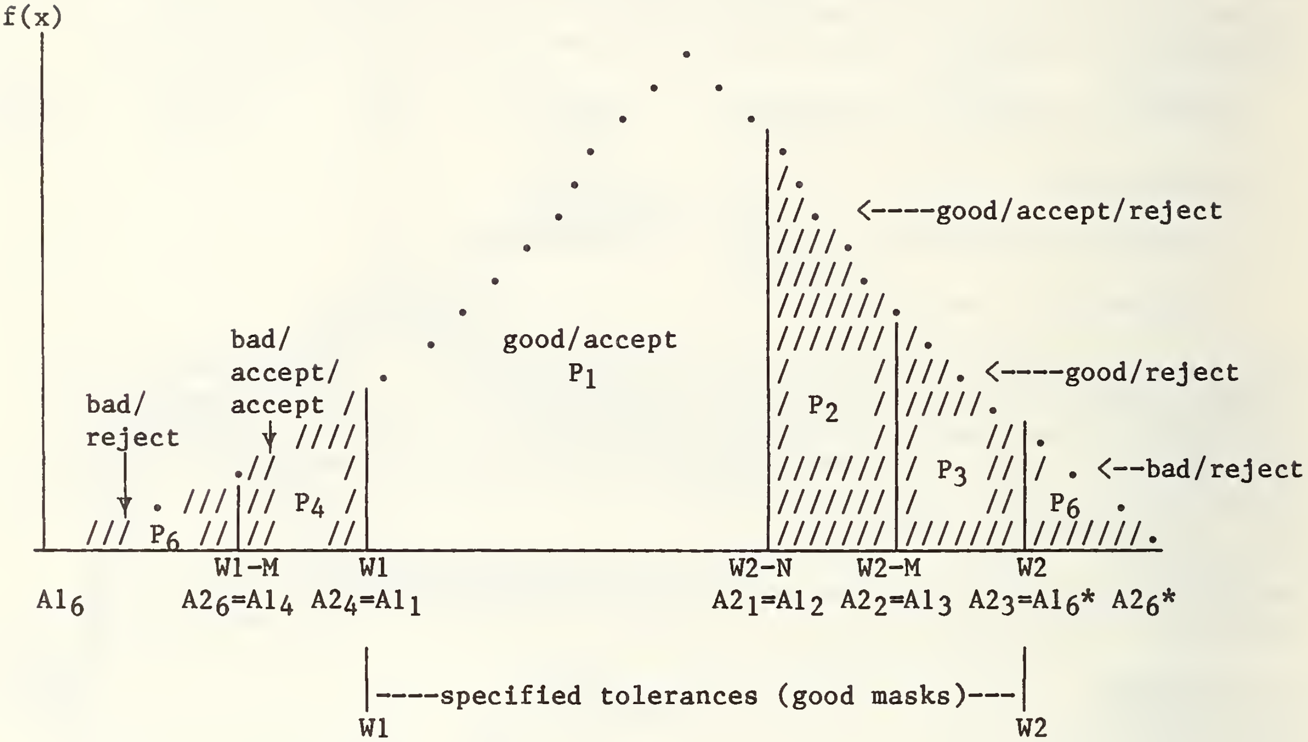
$W1-M \leq x \leq W2-M$, and

$W2-N < x$ or $x < W1-N$

are satisfied if $A1= W2-N$ and $A2=W2-M$ so that for all masks on this path, $W2-N < x \leq W2-M$.

The formulas for $A1_i$ and $A2_i$ for all paths are summarized in table 2.2. The table assumes that measurement biases M and N are small relative to the specified range of linewidths; specifically, $|M|+|N| \leq W2-W1$.

Figure 2.5 Path Probabilities with $A1_i$ and $A2_i$[b]



P_5 (bad/accept/reject) = 0

f(x) = probability density function for mask with respect to linewidths

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[a] This example assumes that the IC producer's measurement bias is greater than the mask shop's measurement bias and that both are positive (N>M>0).

[b] This graph is the same as figure 2.3, but the values for $A1_i$ and $A2_i$ are shown on the x-axis.

3. AN APPLICATION OF THE MASK ACCEPTANCE MODEL

This chapter illustrates an application of the model developed in chapter 2. It estimates how per-mask costs of erroneous photomask measurements would change as a result of measurement improvements, given certain assumptions about the measurement system, products, production levels, and other factors. Effects are estimated for several sets of assumptions.

Table 2.1 in the preceding chapter summarizes the formulas that will be used. The derivation of these formulas was explained in chapter 2. Values for various parameters are given in table 3.1. These values were selected to describe a situation that might plausibly occur in industry, based on discussions with industry and NBS scientists.

3.1 SELECTION OF THE CASE

This section discusses the values given in table 3.1. The case analyzed was chosen to be compatible with the intended use of the SRM 474 and to be reasonably representative of many firms, although it does not represent a statistically average case. It was determined through conversations with semiconductor industry firms and NBS scientists, reading, the trade literature, and other sources.

Masks per year (k). We assume that the hypothetical company being analyzed measures 10,000 masks per year which are used in wafer fabrication. These may include masks for both contact and projection printing of wafers.

Linewidths target value (W). More than half of IC devices produced in 1980 had linewidths from 2 to 5 μm.[1] The base case in this study assumes that target values (W) for photomask linewidths are 3 μm. This is a conservative assumption, since measurement errors are more costly at the smaller linewidths that will become common in the future. (Smaller linewidths are assumed in the sensitivity analysis.)

Tolerances (W1 and W2). Companies interviewed for this study mentioned linewidth tolerances of ±10 percent or in the 0.1 to 0.3 μm range for chromium masks. It is likely that tolerances on photomasks will decline to ±0.1 or ± 0.2 μm. A tolerance of ± 0.25 μm is assumed here, so that the base case mask specifications are W1=2.75 μm and W2=3.25 μm. (Smaller tolerances are used in the sensitivity analysis.)

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[1] Bossung, J.W. and E.S. Muraski, "Advances in Projection Microlithography," Solid State Technology, August 1979, pp. 109-112; Jerke, John M., ed., Semiconductor Measurement Technology: Accurate Linewidth Measurements on Integrated Circuit Photomasks, National Bureau of Standards Special Publication 400-43 (Washington, D.C.: U.S. Government Printing Office, 1980), pp. 3 and 113; and Burggraaf, Pieter, "Photomask Making: Issues vs. Equipment," Semiconductor International, March 1981, p. 30.

Table 3.1 Values Used in the Model - Base Case

			(See section)
Selection of the case			3.1
Lower bound specification for linewidths	W1 = 2.75 µm		
Upper bound specification for linewidths	W2 = 3.25 µm		
Target Value	W = 3 µm		
Mask probability density function[a]	f(x): normally distributed mean (W) = 3 µm st'd dev. (σ_x)=0.1 µm		
Number of masks measured annually	k = 10,000		
Costs of measurement related problems	Masks for projection printing	Masks for contact print.	3.2
Mask remake cost (before better meas.)	C1' = $1,000	$100	
Mask remake cost (after better meas.)	C1" = $1,000	$100	
Costs of resolving dispute (before)	C2' = $100	$ 0	
Costs of resolving dispute (after)	C2" = $ 50	$ 0	
Costs if a bad mask is used (before)	C3' = $2,000	$ 30	
Costs if a bad mask is used (after)	C3" = $2,000	$ 30	
Systematic error			3.3
Mask shop measurement bias: before	M = 0.12 µm		
after	= 0.08 µm		
IC manufacturer measurement bias: before	N = 0.2 µm		
after	= 0.1 µm		
Discounting and time-related variables			3.4
Real discount rate	r = 10%		
Useful life of procedures	t = 6 years		
Years before procedures implemented (with NBS)	s = 1 year		
(without NBS)	s*= 3 years		
Analysis period	T = 5 years		
Single present worth discounting factors for discount rate "r"	SPW_1 = .9091 SPW_2 = .8264	SPW_3 = .7513 SPW_4 = .6830	
Uniform present worth discounting factors for discount rate "r"	UPW_3 = 2.487 UPW_5 = 3.791		

Table 3.1 Values Used in the Model - Base Case (Cont.)

Implementation costs

Added initial implementation cost	$C5 = \$13,460$	
Added annual implementation cost	$C6 = \$\ 6,600$	
Other added implementation costs	$C7_1 = \$\ 6,600$	$C7_1{}^* = \$6,600$
(* indicates without-NBS situation)	$C7_2 = \$\ 6,600$	
Timing of other added costs	$u(1) = 2$	$u(1)^* = 2$
(* indicates without-NBS situation)	$u(2) = 4$	

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[a] Based on the frequency distribution of masks produced with respect to linewidths.

Mask production function [$f(x)$ and σ_x]. We assume that the distribution of masks with respect to linewidths can be approximated by a normal curve with a mean of $W = 3\mu m$ and a standard deviation σ_x.[1] The formula for such a normal curve is as follows:

$$f(x) = \left\{\frac{1}{\sigma_x\sqrt{2\pi}}\right\} e^{-\frac{1}{2}\left(\frac{x-W}{\sigma_x}\right)^2} \tag{14}$$

A 1979 conference paper described a method of producing high quality masks which gave a three-sigma variability of 0.35 μm.[2] In the absence of good information about mask variability, a one-sigma variability (σ_x) of 0.1 μm is assumed for the base case study and varied in the sensitivity analysis.

3.2 COSTS OF MEASUREMENT RELATED PROBLEMS (C1, C2, C3)

Erroneous measurements lead to several types of costs. This section assigns values to costs of disputes, costs of remaking masks, and costs arising from a bad mask being put into use.

Remake cost (C1' and C1"). The mask remake cost used in the base case study is $1,000 for masks intended for projection printing of wafers, both before and after improving measurements. Masks intended for contact printing of wafers are assumed to cost $100. These values were selected based on information from mask producers and other sources concerning typical mask sales prices, but they do not represent statistical averages of mask prices. Projection and contact printing are the most widely used methods for printing wafers. Values were chosen assuming that the masks were chromium because the SRM is designed to improve measurements of antireflective chromium masks.

Dispute resolution cost (C2' and C2") One company interviewed estimated that resolving disputes involving measurements of submicrometer lines probably cost $3,000 to $4,000 per dispute. However, disputes concerning less costly masks, and disputes between divisions of the same company, are likely to cost less to resolve. At $40 per hour, a dispute whose resolution takes one hour of management time each from the mask shop and the mask user would cost $80. For masks intended for projection printing, this is rounded up to C2' = $100 per dispute to account for other expenses such as operator measurement time.

Several companies mentioned that the introduction of the SRM would make disputes easier to resolve. Presumably companies would be able to detect the reason for measurement discrepancies more quickly if they can check their equipment using standardized procedures and NBS standards or secondary

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[1] The method described here could also be used for non-normal distributions. We chose the normal distribution due to lack of data about actual distributions, and to simplify the analysis.

[2] Dan, M.; I. Tanabe; M. Hoga; and S. Torisawa, "Fabrication System of High Quality Hard-Surface Masks for LSI's," Proceedings of Kodak Microelectronics Seminar: Interface '79 (San Diego, October 25-26, 1979).

standards measured on equipment calibrated using NBS standards. This source of cost savings is difficult to quantify. We attribute a savings of $50 per dispute to the availability of the NBS SRM and procedures, so that C" is $50 for masks intended for projection printing. In the sensitivity analysis, this cost saving is reduced.

For masks used in contact printing of wafers, dispute costs are assumed to be zero "before" and "after."

Yield loss cost (C3)

We were not able to obtain adequate data on the costs due to yield loss and other effects of using a bad mask in wafer fabrication. It appears that the effect on yield loss can be substantial; it ranges widely, from almost nothing to a complete loss of yield until the source is detected. The causes of yield loss may be detected and corrected immediately, or the yield loss may persist for months, until the mask is replaced for other reasons. This is especially likely for very slight yield losses.

In the absence of good data, the base case assumes a yield loss cost of $2,000. This would correspond, for example, to a decline in yield from 16 percent to 15 percent for ten days on IC devices valued at $3,200 per day. Such a yield loss due to incorrect mask measurements appears plausible, based on conversations with industry.

The cost of measurement error is lower for masks for contact printing because of the lower costs and reduced use of each mask. The yield loss cost for such masks was assumed to be $30.

3.3 SYSTEMATIC ERROR (M and N)

Since the model in this report assumes perfectly repeatable measurements (no random error), the measurement bias is simply the discrepancy between the true and measured linewidth.[1] The size of bias can be reduced by calibrating to a standard such as the SRM 474.

Bias before calibrating

NBS conducted an interlaboratory test of the NBS calibration procedures.[2] The ten companies involved in the study included mask houses, device manufacturers,

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[1] If there is random error, then the bias or systematic error is the difference between the true linewidth value and the limiting mean of the linewidth measurements, i.e., the mean to which the sample mean approaches as the number of measurements increases. See Ku, Harry, "Statistical Concepts in Metrology," p. 299-23.

[2] Results will be published in Semiconductor Measurement Technology: Interlaboratory Study of Linewidth Measurements for Antireflective Chromium Photomasks, J.M. Jerke, M. Carroll Croarkin, and Ruth N. Varner (Washington, D.C.: National Bureau of Standards, in preparation).

and equipment suppliers. NBS sent mask-like artifacts to the participants for measurement and, later, compared the linewidth measurements reported by industry with the NBS values.

Several types of measurement systems were involved. For opaque lines near 3 μm measured on one widely used type of system, the average offset from the NBS values was 0.16 μm. There were also differences between systems of this type in the amount of offset, averaging .08 μm for opaque 3 μm lines.[1]

Biases and discrepancies in industry before calibrating with the SRM 474 may be greater than those in the interlaboratory study, for three reasons:

(1) in the interlab test, company data were edited for "outliers"--occasional extreme measurements--before determining offsets. For data that had not been edited, average offsets from the true value would frequently be greater; (2) the interlab studies involved firms who were relatively advanced in their linewidth measurement practices; and (3) the companies in the test followed NBS procedures in making the measurements. Even without the SRM, following these procedures would tend to reduce bias.

These data are for a type of linewidth measurement system which is widely used in industry and appears to be intermediate in its accuracy between other types of systems. Therefore, the data for this system are used in selecting the values for measurement bias used in the base case.

Based on the above discussion, we assume that the average offset from NBS is 0.16 μm, and that .08 μm is the difference between the mask shop and IC producer. Thus, the assumed offsets for a mask shop and IC producer are $[0.16 - 1/2\ (.08)]$μm and $[0.16 + 1/2\ (.08)]$μm. Since mask shops tend to be the leaders in mask measurement technology in their organizations, the mask shop is assumed to have the lower offset, $M=0.12$ μm. For the IC producer, the offset, N, is assumed to be 0.20 μm.[2]

Bias after calibrating

The case example in this report concerns a company which has purchased an SRM 474. Most companies will calibrate one microscope with the SRM and then measure secondary standards on this calibrated microscope. From discussions with firms, it appears that few companies followed statistically-based calibration procedures for calibrating their linewidth measurement equipment before

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[1] Croarkin, Carroll; John Jerke; and Ruth Varner, Results of Interlaboratory Study: Lecture Notes (presented at the NBS Training Seminar, "Linewidth Measurement on Integrated Circuit Photomasks and Wafers," July 15-18, 1980).

[2] The assumption that both supplier and customer use the same type of system is a conservative assumption; measurement discrepancies may be larger where measurements are made with different types of systems.

NBS made its recommendations. NBS researchers believe that following these procedures may significantly reduce companies' measurement biases.[1]

However, the biases will probably not be reduced to zero, for several reasons: (1) the SRM itself has an inherent uncertainty of ±.05 μm; (2) in-house standards measured on equipment calibrated with the SRM 474 will have uncertainties greater than that of the SRM; and (3) the calibration curve itself has uncertainty attached to it. Based on discussions with NBS scientists, this paper assumes that offsets are reduced to 0.08 μm for M and 0.1 μm for N.[2]

3.4 DISCOUNTING AND TIME-RELATED VARIABLES (UPW, SPW, r, t, T, s, u(i))

The base case uses a real discount rate, r, of 10 percent, the rate specified for Federal agency use by the Office of Management and Budget.[3] With 10 percent inflation, this would be the equivalent of a 21 percent market rate.[4] Effects of changing the discount rate are shown in the sensitivity analysis.

Useful life and analysis period

The Uniform Present Worth (UPW) factors for discounting equal annual costs and benefits were selected from the table in appendix B for 10 percent and the remaining useful life, "t-s". The factors for discounting other cost and benefit items -- the Single Present Worth (SPW) factors -- were selected from table B.1 for 10 percent and the number of years "u(i)" or "s". These factors are shown in table 3.1.

It is very difficult to predict the useful life of the measurement procedures. A new measurement approach may eventually supersede the NBS approach, or new technologies such as direct writing on wafers with an electron beam may make photomasks less widely used. This study assumes that the NBS results will be useful for six years after 1980 before they become obsolete. Thus, the useful life, t, is six years. It assumes that the company adopts the new procedures in 1981 so that the number of years after 1980 that the new procedures are implemented, s, is one. The analysis period, T, equals "t-s" or 5 years.

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[1] Jerke, J. M.; Croarkin, M. C.; and Varner, R. N., Semiconductor Measurement Technology: An Interlaboratory Study of Linewidth Measurements for Antireflective Chromium Photomasks (Washington, D.C.: National Bureau of Standards, in preparation).

[2] We assume the company keeps the same measurement system, thus neglecting any benefit from NBS influence on choice of system.

[3] U.S. Office of Management and Budget, "Circular No. A-94 Revised," March 27, 1972.

[4] Market rate = (1 + real rate) (1 + inflation rate) - 1.

3.5 IMPLEMENTATION COSTS (C4)

Some costs of implementing NBS results, such as the SRM cost, are relatively easy to determine. Other costs, such as of management planning time, may be difficult to estimate. However, the sensitivity analysis in section 3.8 suggests that the uncertainty connected with the estimates of implementation costs is not of great concern because net benefits predicted from adopting the SRM and NBS procedures appear to be fairly insensitive to implementation costs, at least for the assumptions and parameter values used in this paper. The various costs are discussed below.

Costs of implementing NBS results are calculated for a hypothetical mask shop which measures 10,000 masks per year using 10 measurement systems. Other assumptions describing the hypothetical mask shop are listed in table 3.2. The assumptions were made based on information from two mask houses and from other sources. Implementation costs would probably be different for companies not fitting these assumptions.

Fourteen cost items are listed in table 3.2. Several of them are briefly discussed below.

Startup costs (C5)

The figures in table 3.2 for management time assume that a manager from California attends a week-long training seminar on the East Coast.[1] Other startup costs listed in table 3.2 are management time to train others, operator training, engineer training, and initial equipment calibration.

Hardware changes. No major equipment changes are needed to implement the NBS results on many systems. This case assumes that the hardware cost for implementing the NBS procedures is $16/system, the cost of adding a green filter.

Computer program development. Some companies have spent money writing a computer program to carry out the calibration calculations. However, since NBS provides the listing for such a program, this cost is excluded from the estimates.

SRM. Most companies are likely to purchase only one SRM 474, at a cost of $3,600. A simpler SRM (475) is also being sold for $2,500, but the $3,600 figure is used for this study. It is assumed that the SRM requires replacement every two years due to damage. Its actual life could be much longer with careful handling.

Secondary standards. Most companies will use standards traceable to the SRM 474 for their routine calibrations. Some companies will manufacture or purchase new secondary standards; others will simply remeasure existing standards. We assume the company obtains and measures one new standard for each measurement system, and that standards are replaced every two years.

---

[1] Costs would be reduced for companies attending West Coast seminars, which were initiated by NBS in 1981.

Table 3.2 Mask Shop Implementation Costs

Assumptions

10 measurement systems
1,000 masks measured/system/year
3 operators/system ($10/hour/operator)
2 engineers ($20/hour/engineer)
1 secondary standard/system

1 SRM
$40/hour management cost
10% real discount rate

Item	Added Cost/Unit	Added Cost per Company ($)
Startup Costs (C5)		
Mgt. learning & planning	Travel $1,000 60 hours X $40/hour	3,400
Mgt. time to train others	20 hours X $40/hour	800
Hardware	10 systems X $16/system	160
SRM		3,600
Computer program	0 hours	0
Operator training	5 hours X $10/hour X 30 oper.	1,500
Engineer training	20 hours X $20/hr. X 2 engrs.	800
Mfrg. in-house standards	10 standards X $100/standard	1,000
Measuring in-house stds.	10 standards X $200/standard	2,000
Initial equip. calibrat.	10 systems X $20/system	200
Subtotal (C5)		13,460
Equal annual costs (C6)		
Production meas.	10,000 masks X .05 hrs./mask X $10/hr.	5,000/yr.
Checking and adjusting equipment:		
engineer:	10 syst. X 2 hrs/syst. X $20/hr.	400/yr.
oper.:	10 syst. X 12 hrs/syst. X $10/hr.	1,200/yr.
Subtotal (C6)		6,600/yr.
Other ongoing costs ($C7_i$)		
SRM replacement		3,600/two yrs.
Stds replacement	10 stds. X $300/std./two years	3,000/two yrs.
Subtotal (C7)		6,600/two yrs.

Ongoing costs (C6 and C7)

Production measurements. This case assumes a few extra minutes per mask are needed to measure according to NBS procedures. This figure is subject to much uncertainty. It is also relatively important, since it is a cost which continues over the life of the procedures.

Other ongoing costs are for SRM and secondary standards replacement. These are listed in table 3.2.

Table 3.2 summarizes the breakdown of costs. The total initial cost is \$13,460. Ongoing costs are \$1,600 per year for periodic recalibration and adjustment, \$6,600 every two years for replacement of standards, and \$5,000 per year for added time for routine mask measurements.

Calculating implementation costs (C4)

Implementation costs (C4) are calculated using equation (7) in table 2.1 and the values in table 3.1. For a company implementing in 1981, the analysis period is 1981-1985. The total costs of about \$88,000 (present value) are averaged over 50,000 masks (five years X 10,000 masks/year) to get the discounted average cost per mask of \$1.76.[1]

Had NBS results not been available, this company would implement new measurement procedures in 1983, according to an assumption discussed in section 3.7. However, the relevant analysis period is still 1981-1985, and costs are averaged over the 50,000 masks that are produced in this period. Costs per mask would be about \$1.06.[2]

3.6 CALCULATING THE COST SAVINGS (B)

We have now assigned values to all the variables in the model and calculated implementation costs, C4, for the hypothetical company. The values assigned are shown in table 3.1. To determine benefits per mask for an IC company with an in-house mask shop, the next step is to calculate the path probabilities P_2 through P_6 using the formulas for $A1_i$ and $A2_i$ from table 2.2 for N>M>0, the equation for P_i in table 2.1, and the parameter values in table 3.1.

Calculations for P_2 through P_6, before and after improving measurements, are shown in table 3.3. For example, the probability of good/accept/reject (P_2) is .21174 or 21 percent before improving measurements, but falls to .02224 or 2 percent after improving measurements. These probabilities are illustrated in figure 3.1.

---

[1] $C4 = \frac{2}{10,000\ (5)}[\$13,460+\$6,600(3.791)+\$6,600(.8264)+\$6,600(.6830)].9091=\$1.76.$

[2] $C4^* = \frac{2}{10,000\ (5)}[\$13,460+\$6,600(2.487)+\$6,600(.8264)].7513=\$1.06.$

Table 3.3 Calculating Path Probabilities[a]

$$P_2' = \int_{W2-N}^{W2-M} f(x)dx = \int_{3.05}^{3.13} f(x)dx = .21174$$

$$P_3' = \int_{W2-M}^{W2} f(x)dx = \int_{3.13}^{3.25} f(x)dx = .09059$$

$$P_4' = \int_{W1-M}^{W1} f(x)dx = \int_{2.63}^{2.75} f(x)dx = .00610$$

$$P_5' = 0$$

$$P_6' = \int_{0}^{W1-M} f(x)dx + \int_{W2}^{\infty} f(x)dx = \int_{0}^{2.63} f(x)dx + \int_{3.25}^{\infty} f(x)dx = .00632$$

$$P_2'' = \int_{W2-N}^{W2-M} f(x)dx = \int_{3.15}^{3.17} f(x)dx = .02224$$

$$P_3'' = \int_{W2-M}^{W2} f(x)dx = \int_{3.17}^{3.25} f(x)dx = .03836$$

$$P_4'' = \int_{W1-M}^{W1} f(x)dx = \int_{2.67}^{2.75} f(x)dx = .00573$$

$$P_5'' = 0$$

$$P_6'' = \int_{0}^{W1-M} f(x)dx + \int_{W2}^{\infty} f(x)dx = \int_{0}^{2.67} f(x)dx + \int_{3.25}^{\infty} f(x)dx = .00669$$

---

[a] The limits of integration come from table 2.2 for N>M>0 and parameter values come from table 3.1. In this example, f(x) is a normal curve with standard deviation $\sigma_x = 0.1$ µm and mean W = 3 µm. A slight variation on the formula given in table 2.1 for P_i is needed to compute P_6 since it equals the sum of two sections under the probability density function. For the method of calculating areas under a normal curve, see a statistics text such as Mills, Frederick C., Statistical Methods, third edition (New York: Hold, Rinehart, and Winston), 1955, pp. 157-159.

For the base case, as table 3.4 shows, the gross undiscounted cost savings (before subtracting implementation costs) per mask due to improved measurements are \$262.16 per mask. For the less expensive masks for contact printing, the savings are \$24.15 per mask.

Discounted net benefits per mask for a company measuring 10,000 masks/year were computed using equation (1) in table 2.1. The savings are \$178.94 for masks intended for projection printing of wafers and \$14.88 for masks used in contact printing.[1]

These estimates of savings do not take into account progress that might have been made in the absence of the NBS research. Cost savings that might have occurred had NBS not conducted its research, also shown in table 3.4, are discussed in the next section.

Comparison with the "without NBS" situation

The net benefits calculated so far show the savings when companies adopt improved measurement technology. However, even without NBS, companies would eventually adopt improved measurement technologies. Therefore, costs and benefits if companies had acquired improved measurement technology from some other source were calculated.

Values are assigned to s*, C7*, and u(i)* to reflect the "without NBS" situation. Without NBS, improved methods would have been available three years later than they actually were so that $s^* = 3$. This assumption, which is thought to be conservative, was based on comments by an industry metrologist.

Without NBS, cost item $C7_1^*$ is the same as cost item $C7_1$, but there is no $C7_2^*$. This is because $C7_2^*$ would occur in four years, one year after the end of the useful life of the measurement procedures. Similarly, $u(1)^* = 2$ but there is no $u(2)^*$.

Implementation costs and net benefits were computed using equations 8 and 2 in table 2.1 and values for s*, $C7_i^*$ and u(i)* in table 3.1. Other values were unchanged. Implementation costs without NBS (C4*) were \$1.06 per mask. Net benefits per mask without NBS (B*) were \$96.91 for masks for projection printing and \$7.96 for masks for contact printing.

For companies who would adopt NBS procedures in 1981, the without-NBS alternative would have been to adopt new procedures in 1983. Therefore, the cost savings for adoption in 1983 are subtracted from cost savings for adoption in 1981. The added cost savings per mask due to NBS for masks for projection printing are \$82.03.[2]

---

[1] $$B = (\$342.02 - \$79.86)\,\frac{3.791}{5}\,(.9091) - \$1.76 = \$178.94.$$

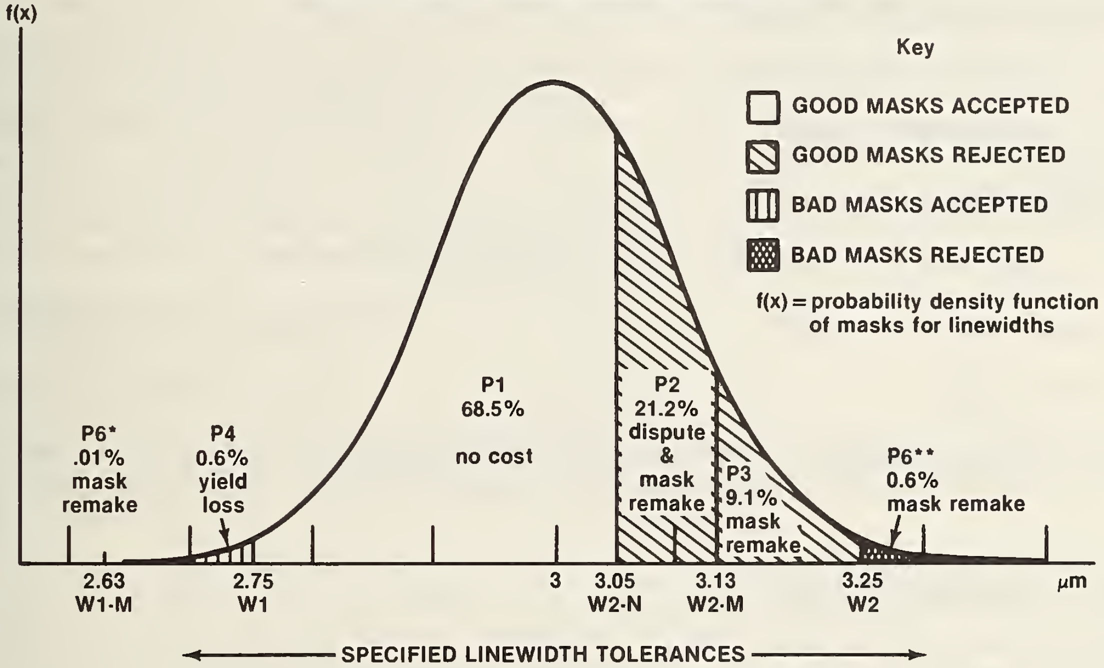
$$B = (\$31.05 - \$6.90)\,\frac{3.791}{5}\,(.9091) - \$1.76 = \$14.88.$$

[2] $B - B^* = \$178.94 - \$96.91 = \$82.03.$

Figure 3.1

PROBABILITIES OF VARIOUS MASK MEASUREMENT OUTCOMES

BEFORE IMPROVED MEASUREMENTS



AFTER IMPROVED MEASUREMENTS

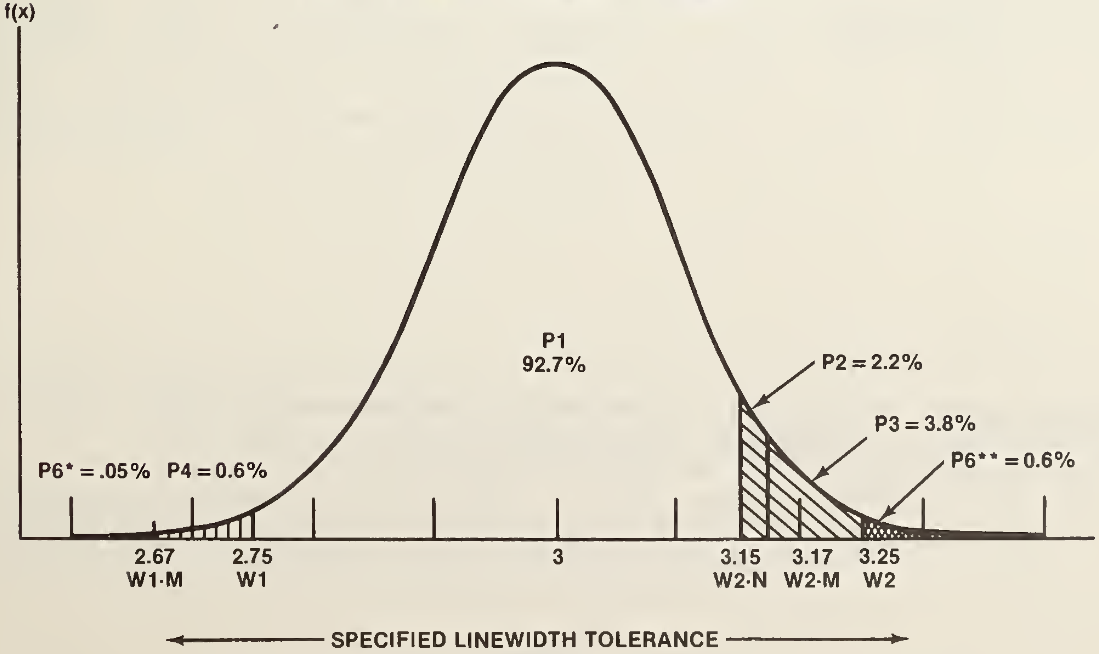


Table 3.4 Gross Undiscounted Savings (Base Case)[a]

Masks for projection printing

$$C' = C1' (P_2' + P_3' + P_5' + P_6') + C2' (P_2' + P_5') + C3'P_4'$$

$$= 1{,}000 (.21174 + .09059 + 0 + .00632) + 100 (.21174 + 0) + 2{,}000 (.0061)$$

$$= \$342.02/\text{mask}$$

$$C'' = C1'' (P_2'' + P_3'' + P_5'' + P_6'') + C2'' (P_2'' + P_5'') + C3''P_4''$$

$$= 1{,}000 (.02224 + .03836 + 0 + .00669) + 50 (.02224 + 0) + 2{,}000 (.00573)$$

$$= \$79.86/\text{mask}$$

$$C' - C'' = \$262.16/\text{mask}$$

Masks for contact printing

$$C' = 100 (.21174 + .09059 + 0 + .00632) + 0 + 30 (.0061)$$

$$= \$31.05/\text{mask}$$

$$C'' = 100 (.02224 + .03836 + 0 + .00669) + 0 + 30 (.00573)$$

$$= \$6.90/\text{mask}$$

$$C' - C'' = \$24.15/\text{mask}$$

---

[a] Savings before discounting or subtracting implementation costs. Values are from tables 3.2 and 3.8. The formulas are from table 3.1.

(The company saves the full $178.94, of course, but only part of this is credited to NBS, since some savings would have been realized even without NBS.) For contact printing, the added cost savings are $6.92.[1]

It is important to remember that these figures do not necessarily represent the cost savings for any particular company, or the average savings from using NBS procedures. Rather, they are examples of the amount of savings that might occur in a specific hypothetical situation. The model used is in some ways a simplification of the real world, and in any case it only shows what would happen for a particular situation. Also, the NBS linewidth measurement research has major effects which are outside the scope of this study. Thus, the kinds of cost savings estimated here may well represent only a fraction of the overall benefits from the NBS research.

3.7 SENSITIVITY ANALYSIS

Benefits credited to NBS

The amount of benefits attributed to NBS was sensitive to the assumed lag by industry behind NBS. Results of the sensitivity analysis are illustrated in figure 3.2.

In the base case, NBS technology is available three years earlier than similar technology would be available from other sources, i.e., in 1980 rather than 1983. In this case, net benefits credited to NBS were $82 per mask. If NBS technology were available only two years earlier, net benefits credited to NBS would decrease to $43 per mask. If NBS technology were available four years earlier, the benefits attributed to NBS would increase to $117 per mask. If NBS technology were available six years earlier, the entire $179 of per-mask benefits would be attributed to NBS since the life of the procedures is assumed to be six years.

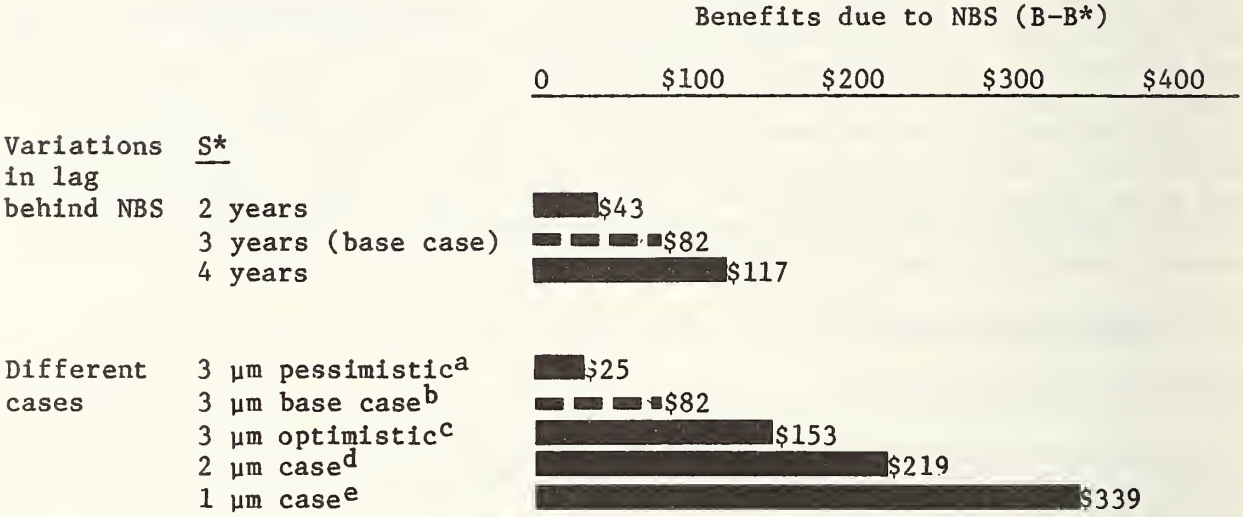
The amount of benefits credited to NBS was sensitive to the selection of other variables. This is illustrated in figure 3.2. For example, under a "pessimistic" case involving 3 μm lines, the net benefits due to NBS fell to $25 per mask.[2] In an "optimistic" case involving 3 μm lines, the net benefits increased to $153 per mask. For cases involving 2 μm and 1 μm lines, benefits due to NBS were $219 and $339 per mask, respectively.

---

[1] $B - B^* = \$14.88 - \$7.96 = \$6.92$.

[2] In this context, the "pessimistic" case is the one likely to result in small benefits from improved measurements. Thus, smaller variability in masks with respect to linewidths would be part of the "pessimistic" case even though it is a desirable result for the manufacturer.

Figure 3.2 Sensitivity Analysis: Benefits due to NBS (B-B*)



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[a] σ_x=.05, M'=.09, N'=.15, C1=500, C2"=90, C3=200

[b] W2-W1=.5, σ_x=.1, M'=.12, M"=.08, N'=.2, N"=.1, C1=1000, C2'=100, C2"=50, C3=2,000

[c] W2-W1=.4, N'=-.2, N"=-.1, C2=0, C3=2,000

[d] W2-W1=.4, σ_x=.05, C2'=500, C2"=250, C3=5,000

[e] W2-W1=.2, σ_x=.05, C1=2,000, C2'=500, C2"=250, C3=5,000

Total benefits including those not credited to NBS

We also calculated the sensitivity of the benefits from improved measurements to changes in assumed values without subtracting out the benefits that would have occurred even without NBS. Figure 3.3 shows the results. The letters below refer to parts of figure 3.3.

A. Measurement bias (M, N)

As is shown in part A of figure 3.3, the net benefits per mask were very sensitive to changes in the amount by which measurement bias is reduced. Where biases were opposite in sign, improved measurements were particularly beneficial (benefits rose to \$220) because they substantially reduced measurement differences between companies.

A few combinations of initial errors and improvements gave very slightly negative results. For example, net benefits per mask were very slightly negative (-\$2) in a case where there was an improvement for the IC producer but not for the mask maker. Also, where there was a high level of bias to start with, e.g., around 0.5 μm, a reduction in bias led to very slightly negative benefits per mask of -\$2.

In certain situations, improving measurements may reduce one kind of cost but increase another. For example, companies may reduce the number of bad masks accepted, but increase the number of disputes. The net impact depends on which kind of problem is most costly.

B. Tolerances (W1, W2, and W); standard deviation of mask distribution (σ_x)

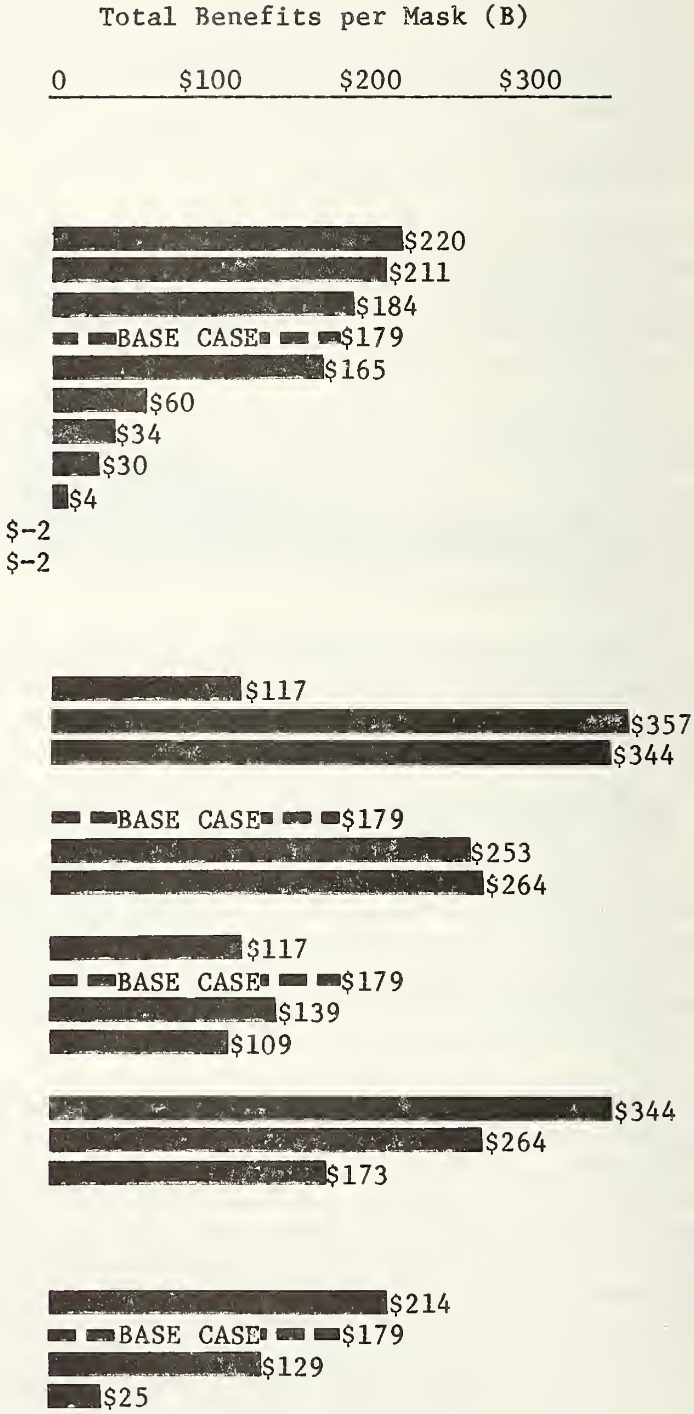
Part B of figure 3.3 shows that the effects of improved measurements varied with the tolerance range W2-W1 but not with the absolute level of the target value, W. As the spread W2-W1 narrowed from 0.5 μm to 0.2 μm, the benefits of improved measurements increased from \$179 to \$264 per mask for mask variability standard deviation (σ_x) of 0.1 μm. For σ_x=.05 μm, the relationship was not as clearcut, as figure 3.3 part B shows.

The degree of control of between-mask linewidth variability (the one-sigma of the mask distribution, σ_x) was very significant. Improving production control by changing σ_x from 0.3 μm to 0.1 μm made it more cost-effective to improve measurements, increasing savings from \$109 to \$179 per mask. This may be because where control is relatively poor (σ_x is large), many masks are so far out of spec that they are correctly determined to be out of spec even with measurement error. But where control is better, more masks are close to the tolerance limits, so that there may be more acceptance mistakes due to measurement error. On the other hand, where control is extremely good, most masks may be so far within specs that even with measurement error they are accepted.

C. Discount rate (r)

Figure 3.3 part C shows that changing the discount rate had a significant effect on net benefits. For example, reducing the real rate of return from

Figure 3.3 Sensitivity Analysis: Total Benefits



A. Measurement Biases (μm)

M'	M"	N'	N"	Total Benefits per Mask (B)
.12	.08	-.2	-.1	$220
.12	.03	.2	.05	$211
0	0	.2	.1	$184
.12	.08	.2	.1	BASE CASE $179
.2	.1	.12	.08	$165
.4	.36	.48	.38	$60
.12	.08	0	0	$34
.12	.11	.2	.19	$30
.12	.08	.2	.2	$4
.2	.2	.12	.08	$-2
.5	.46	.58	.48	$-2

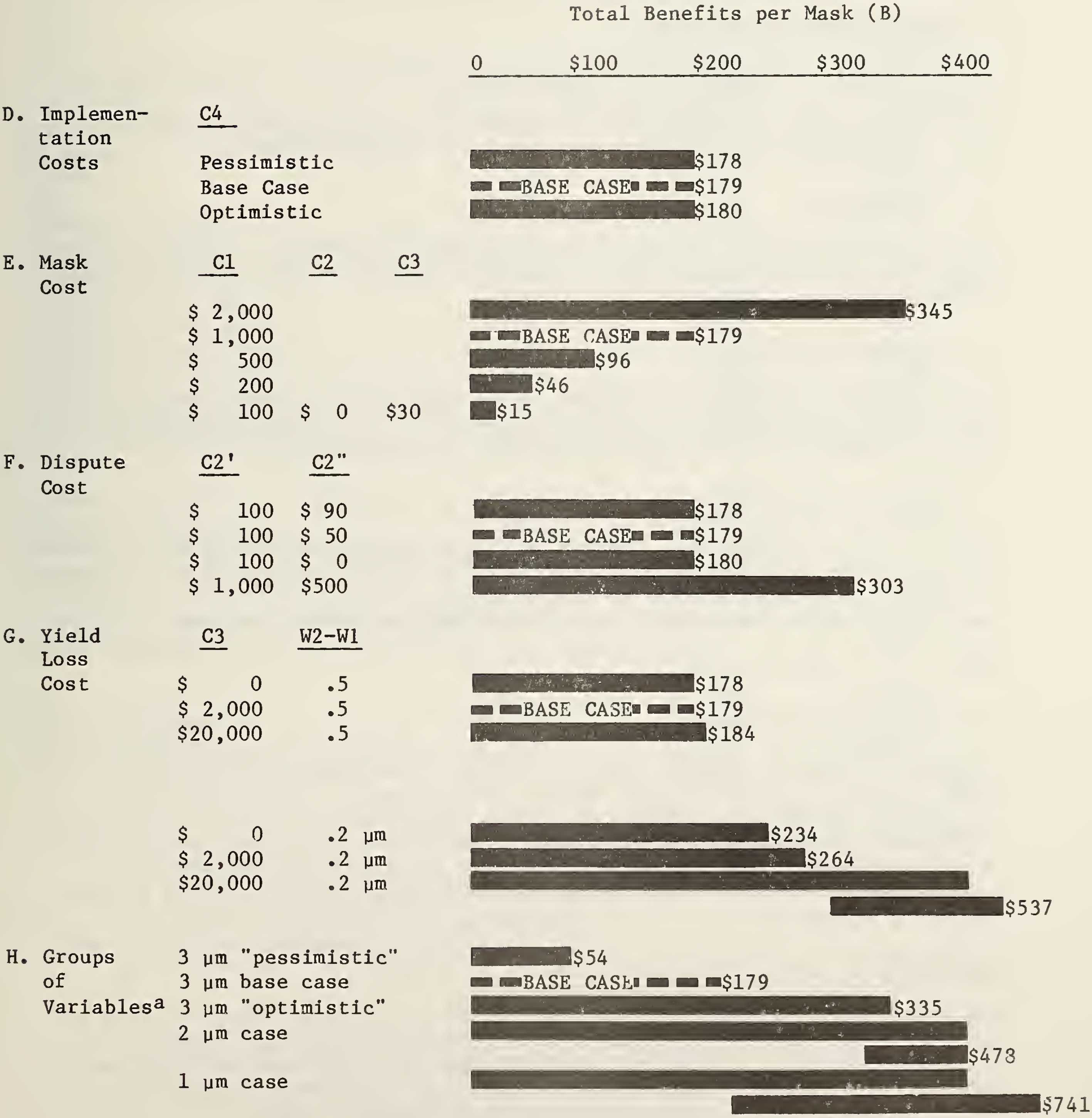
B. Tolerances, Standard Deviation of Mask Distribution(μm)

W2-W1	σx	Total Benefits per Mask (B)
.5	.05	$117
.4	.05	$357
.2	.05	$344
.5	.1	BASE CASE $179
.4	.1	$253
.2	.1	$264
.5	.05	$117
.5	.1	BASE CASE $179
.5	.2	$139
.5	.3	$109
.2	.05	$344
.2	.1	$264
.2	.2	$173

C. Discount Rate

r	Total Benefits per Mask (B)
5%	$214
10%	BASE CASE $179
20%	$129
100%	$25

Figure 3.3 Sensitivity Analysis: Total Benefits (Continued)



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[a] See figure 3.2 for parameter values.

10 to 5 percent (5 percent is equivalent to a 15.5 percent market rate if there is 10 percent inflation) increased net benefits per mask from \$179 to \$214 because it did not discount future benefits so heavily. However, even at very high rates of discount (100 percent), net benefits were still positive.

D. Implementation costs (C4)

The sensitivity to implementation costs was analyzed for an optimistic and pessimistic set of assumptions, listed in table 3.5. As figure 3.3 part D illustrates, the net benefits were very insensitive to implementation costs, since implementation costs were very small relative to benefits.

E. Mask cost (C1)

Increasing the mask cost from \$1,000 to \$2,000 significantly increased the net benefits of improved measurements, from \$179 to \$345 per mask. This is illustrated in figure 3.3 part E.

F. Dispute cost (C2)

The results are sensitive to changes in the reduction of dispute costs (C2'-C") only when the magnitude of reduction is large. If improving measurements reduces dispute costs from \$1,000 to \$500, net benefits are \$303 per mask.

G. Yield loss cost (C3)

Figure 3.3 part G shows that changes in yield loss had remarkably little effect on measured net benefits when the tolerance range (W2-W1) was 0.5 µm. However, narrowing the tolerance range to 0.2 µm (e.g., a range of 1.9 to 2.1 µm) made the benefits much more sensitive to the estimate of yield loss cost. In this case, increasing the yield loss cost from \$2,000 to \$20,000 increased benefits from \$264 to \$537 per mask.

H. Groups of variables

Variables were also changed several at a time. For example, for a tolerance range of ±.25 µm, such as might apply to a 3 µm mask, a pessimistic set of assumptions (described in figure 3.2) gave net benefits of \$54 per mask, still very good. An optimistic set of assumptions for the "3 µm case" gave benefits of \$335 per mask. When values were selected for a hypothetical device with 2 µm lines, net benefits increased greatly, to \$478 per mask. This is shown in figure 3.3 part H.

Conclusion

The sensitivity analysis suggests that for the underlying model described in chapter 2, the benefits of improved measurements are strongly positive, and even large errors in estimating many variables would probably not make the net effects negative. Sensitivity to changes in the underlying model (e.g., modifying the model to allow for random error) was not tested.[1]

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[1] See suggestions for further research in chapter 6.

Table 3.5

Values Used in Sensitivity Analysis of Implementation Costs

Cost Item	Base Case ($)	Pessimistic Case ($)	Optimistic Case ($)
Management learning & planning	3,400	4,000	1,000
Management time to train others	800	1,600	400
Hardware	160	160	160
SRM	3,600	3,600	3,600
Computer program	0	5,000	0
Operator training	1,500	3,000	300
Engineer training	800	800	800
Standards manufacturer	1,000	1,000	500
Standards measurement	2,000	2,000	1,250
Initial calibration	200	2,000	200
TOTAL INITIAL COSTS (C5)	13,460	23,160	8,210
Periodic checking of equipment	1,600/yr.	1,600/yr.	750/yr.
Routine measurement	5,000/yr.	10,000/yr.	0
Secondary standards replacement		3,000/yr.	
TOTAL ANNUAL COSTS (C6)	6,600/yr.	14,600/yr.	750/yr.
OTHER COSTS [C7(i)]:			
SRM replacement	3,600[a]	3,600[a]	3,600[a]
SRM replacement	3,600[b]	3,600[b]	3,600[b]
Secondary standards replacement	3,000[a]	3,000[a]	1,750[c]
Secondary standards replacement	3,000[b]	3,000[b]	

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[a] Two years after implementating new procedures.
[b] Four years after implementing new procedures.
[c] Three years after implementing new procedures.

4. NBS TECHNOLOGY: DIFFUSION AND QUALITATIVE IMPACTS

The first part of this chapter presents evidence on the extent to which the SRM 474 and NBS procedures for measuring photomask linewidths are used in the U.S. semiconductor industry. The second part qualitatively describes some effects of the NBS research which were not quantified for this report.

4.1 TRANSFER OF NBS RESULTS TO INDUSTRY

The NBS "Market"

It was not feasible within the resources available for this study to estimate dollar values for aggregate national impacts of NBS linewidth measurement research. However, some data on diffusion of results and the number of masks shipped may help put the per-mask benefits mentioned earlier into perspective.

The potential market for the NBS photomask linewidth measurement results depends on the number of photomasks measured each year. (Wafer measurement applications are not considered here.) The NBS SRM 474 and procedures are intended to apply to chromium masks. Information from Dataquest Inc. suggests that, for 1979, the number of chromium masks used in projection printing of wafers was about 25,000 and the number of chromium masks used for contact printing was about 2.6 million.

NBS data suggests that the majority of companies in relevant parts of the semiconductor industry make at least some use of NBS's linewidth research results. At yearend 1980, companies accounting for roughly 85 percent of mask manufacturing, including IC manufacturers, were known to make some use of NBS results.[1] Undoubtedly many other companies also use the NBS results.

NBS has transferred research results to users in the following ways:

SRM 474 sales. As of yearend 1980, NBS had received orders for linewidth SRMs from 16 IC manufacturers, four independent photomask manufacturers, three linewidth measurement equipment and standards manufacturers, and one firm

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[1] Dataquest provided us with values of 1979 silicon consumption for companies with captive IC manufacturing facilities. Based on their workshop attendance, interlaboratory study participation, and SRM purchases, companies which account for about 90 percent of the value of silicon purchases are known to make some use of NBS linewidth measurement results. (Some others probably also use NBS results.) In addition, out of ten leading merchant IC manufacturers, nine are known to make some use of the NBS results.

Twenty-three percent of masks are manufactured by independent mask houses. The rate of NBS research use by mask houses is not known; therefore, we conservatively assume a rate of only 50 percent. Using these figures, the proportion of companies, by mask volume, known to be using NBS linewidth measurement techniques would be at least 50 percent X 13 percent + 90 percent X 87 percent = 85 percent. This assumes that mask volume is proportional to silicon volume for the IC manufacturers.

outside the semiconductor industry.[1] Out of 13 companies contacted which have received or ordered the SRM, 11 said they would standardize on the SRM company-wide and two (both large companies) said they will standardize at some, but not necessarily all, company locations.

Seminars and interlaboratory studies. From 1977 through 1980, NBS conducted four seminars for industry concerning procedures for setting up and calibrating linewidth measurement equipment.[2] Also, ten companies were exposed to NBS linewidth measurement technology when they participated in two interlaboratory studies in the 1977-1980 period.

The list of SRM purchasers, seminar attendees, and interlaboratory study participants shows some of the companies who make use of NBS linewidth measurement results. At yearend 1980 there were about 66 companies at 87 locations involved with NBS in one or more of these ways. Table 4.1 shows the types of organizations involved.

Publications. Over 700 people at 189 organizations have asked specifically to receive publications related to NBS linewidth research, including 59 IC manufacturers and/or buyers, 22 independent photomask manufacturers, 17 microscope and measurement systems manufacturers, 11 government agencies, 25 foreign organizations, 9 universities, and 46 others (including organizations whose activities were not determined).

Other methods of direct transfer to industry. NBS scientists have also transferred linewidth measurement results to industry through phone calls, talks presented at conferences, industry visits to NBS, visits by NBS people to companies, and interactions at meetings of American Society for Testing and Materials (ASTM) standards committees. (NBS research will be the basis for three ASTM standards related to linewidth measurements.)

4.2 SECONDARY DISSEMINATION OF NBS RESEARCH RESULTS

Companies also learn about NBS linewidth measurement technology indirectly, as was illustrated in figure 1.3 in chapter 1. For example, linewidth measurement systems manufacturers frequently recommend NBS practices to their customers. One part of a company may share NBS technical findings with other parts of the company. Photomask suppliers often share NBS recommendations with their customers. And information moves among companies through mobility of people familiar with NBS research results.

In addition, non-NBS authors reference NBS findings in articles and conference papers. Although a computerized search[3] turned up only ten citations to NBS

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[1] As of January 6, 1981, NBS had sold 58 linewidth SRMs.

[2] Two more seminars were held in 1981. Ninety-four different organizations have been represented at all the seminars through 1981.

[3] Science Citation Index (Philadelphia: Institute for Science Information).

Table 4.1

Companies Participating in Interlab Tests, Attending Seminars, or Ordering SRM (through 1980)

	Companies Represented		Company Locations Represented	
Type of Firm	Number	Percent	Number	Percent
IC device manufacturer	34	52	51	59
Measurement systems supplier	10	15	12	14
Mask house	6	9	6	7
Other, including government	16	24	18	20
Total	66	100%	87	100%

Source: Computed from CEEE lists of seminar attendees, companies ordering SRMs, and companies participating in interlaboratory tests. Many companies were involved in more than one way. The number of company locations represented is greater than the number of companies because some companies sent employees from plants at several locations.

linewidth articles by non-NBS authors through October 1980, this is probably a very incomplete reflection of the extent to which NBS linewidth research is referenced. For example, several conference papers which reference the NBS work were not listed in the Science Citation Index.

Secondary standards

NBS results are transmitted indirectly to industry through the use of secondary standards which are related to an SRM 474 through direct calibration. One company may have a dozen or more such secondary standards related to the SRM 474.

There are also a few commercial suppliers of linewidth measurement standards to the semiconductor industry. As of January 1981, the major independent supplier had shipped about 100 standards related to an SRM 474, and had recalibrated 20 standards for customers who returned standards previously purchased. In addition, at least one manufacturer of linewidth measurement equipment supplies standards related to the SRM 474 to customers, and as of yearend 1980, at least one other equipment manufacturer was planning to do so.

4.3 OTHER EFFECTS OF NBS LINEWIDTH MEASUREMENT RESEARCH

NBS linewidth measurement research has had many effects which are not quantified in this report. Some of these "other effects" may involve far greater economic benefits than the effects quantified. These other effects are summarized in this section.

Repeatability. In addition to reducing measurement bias, NBS measurement procedures are designed to improve the repeatability or consistency of linewidth measurements.

Discussions with industry indicate that at a number of companies, NBS has had a significant effect on measurement practices related to repeatability such as use of Kohler illumination, filtered green light, a two-thirds condenser-to-objective numerical aperture ratio, and other practices.[1]

However, we were not able to determine quantitative effects of NBS recommendations on repeatability. NBS researchers believe that following the NBS procedures may improve "3-sigma repeatability" by as much as 1 µm for image-shearing systems.[2] One company suggested that improvements might be large (e.g., a decrease in variability from 0.5 µm to .05 µm) for companies which previously had poor measurement practices but slight for companies with

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[1] Kohler illumination is a type of illumination for optical microscopes which provides uniform illumination, reduces stray light, and results in bright images with good contrast. A condenser is a microscope lens which collects light to illuminate the object being measured. An objective is a lens which forms an image of the object. The numerical aperture is a computed value used to describe the resolving power of the microscope.

[2] Nyyssonen, Diana, November 21, 1980 conversation.

previously good practices. Generally, the companies queried did not appear to have collected and analyzed measurement data in a way that would show the repeatability effects of adopting NBS recommendations.

Wafer linewidths. Some of NBS's photomask linewidth measurement research has also helped improve measurements on wafers. (Current NBS research is specifically concerned with wafer linewidth measurements.)

Better wafer measurements can provide substantial cost savings through improved yields and other benefits. For example, one company responding to a survey conducted for NBS by Charles River Associates reported benefits of $200,000 for 1980 as a result of improved linewidth measurements on wafers due to NBS research.[1]

Product performance. Improved measurements reduce the barrier to production of IC devices with finer lines. For example, one company told us it was able to produce IC devices for research purposes with finer geometries as a result of better linewidth control on photomasks due to applying NBS measurement procedures. Shrinking circuits improves device performance in several important ways, including increasing speed, reducing the space required for a device, reducing energy required to operate the device, and reducing IC manufacturing costs.

Product reliability. NBS researchers believe that improved linewidth measurements also lead to better field reliability of IC devices. This view is corroborated by companies responding to the survey mentioned above conducted by Charles River Associates.

Measurement equipment design. NBS work has affected the design of commercially marketed linewidth measurement systems. According to NBS scientists involved in the project, NBS work has stimulated several major changes in design of some measurement systems, including adjustable threshold for line edge, fine focus control, mercury arc lamps, and use of CRT output in setting video levels for video image scanning systems.[2] For example, one equipment manufacturer referenced NBS work as the basis for the method of line edge selection used in its scanning system.[3]

Measurement equipment selection. NBS work has affected measurement equipment selection. For example, one company told us it avoided a $300,000 expenditure for new measurement equipment because NBS research helped them to make adequate measurements with existing systems.

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[1] Results were reported in Productivity Impacts of NBS R&D: A Case Study of the Semiconductor Technology Program by Charles River Associates (National Bureau of Standards: Washington, D.C., 1981).

[2] Nyyssonen, Diana, January 26, 1981 conversation.

[3] Coates, Vincent, "Computerized Optical System for Precision Line Width Measurements," paper presented at the Microelectronics Measurement Technology Seminar, San Jose, CA, February 7, 1979.

In other cases, companies have decided to replace their equipment with more advanced measurement systems as a result of NBS work, and some companies have used the SRM 474 in evaluating competing systems.

International competitiveness. Better linewidth measurements resulting from NBS research are likely to improve the international competitiveness of U.S. semiconductor firms. Although foreign organizations have access to NBS research results, e.g., through publications and through their American subsidiaries, it seems likely that dissemination of NBS results will be more rapid among U.S. firms.

Other benefits. Other benefits of NBS research within the semiconductor industry include better ability to tune and characterize photolithography equipment used to produce ICs and photomasks. Potential applications outside the semiconductor industry include measurements of the following: computer magnetic tape head gaps; metal fatigue; scratches and digs in optical glass; reticles of various types such as those used for star tracking; laser recordings; and medical and biological specimens.[1]

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[1] Nyyssonen, D. and R. E. Swing, Theory and Use of Optical Microscopes for Linewidth Measurements on IC Photomasks and Wafers, July 15, 1980 (draft paper presented at the July 1980 linewidth measurement workshop held at National Bureau of Standards, Gaithersburg, Md.), p. 1-1.

5. RESEARCH COSTS[1]

This chapter presents estimates of NBS's cost of conducting its linewidth measurement research. As table 5.1 shows, the estimated present value of NBS photomask linewidth measurement expenditures for FY 1974 through FY 1980 was about $2.2 million. This was derived as follows:

1. Data were obtained on actual NBS expenditures for research related to both photomask and wafer linewidth measurements. The primary source of data on expenditures from FY 1974, when the project began, through FY 1978 was files maintained by a scientist involved in the project.

   For FY 79 and 80, direct labor and overhead charges were found by contacting scientists who had worked on the project to determine the percent of their time spent on this project. Capital equipment and other expenditures for FY 79 and 80 were obtained from financial ledgers of the Center for Electronics and Electrical Engineering.

   Some NBS expenses were recovered through fees to industry and so are not included in research costs. For example, the SRM 474 is sold for $3,600, which covers direct costs of producing and measuring an individual SRM. It does not include any margin to repay NBS for the measurement research.

   Cost data are also available from NBS computerized accounting records. However, securing accurate cost data through the NBS accounting system was difficult because of problems in identifying the appropriate cost centers. In some cases, linewidth project costs were combined in one cost center with expenditures on other projects. Also, the change in cost centers over time made the "audit trail" more intricate. Had data been available by project areas, it would have been much easier to estimate research costs.

2. The percent of total linewidth measurement research which was related to photomask mesurements (as opposed to wafer measurements) was estimated by the linewidth measurement research project leader. For example, in FY 80, 20 percent of the research was related to photomasks with the rest being related to wafer measurements. Multiplying by these figures showed photomask-related expenditures of $1,335,756 for the seven-year period.

3. All amounts in column 5 have been expressed in 1980 dollars to adjust for inflation since 1973. Inflation factors for labor and overhead were obtained from the U.S. Office of Personnel Management. Inflation factors for "measuring and integrating instruments" were obtained from the Bureau of Labor Statistics and applied to expenditures on equipment and other items.

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[1] The research for this chapter was conducted primarily by Michael Usle, presently a graduate student at Brigham Young University.

Table 5.1 NBS Research Expenditures

Fiscal Year (1)	Linewidths research spending[a] ($) (2)	Percent for photomask research[b] (%) (3)	Dollars for photomask research ($) (4)	Inflated to 1980 dollars[c] (5)	Compounding Factor[d] (6)	Present Value ($) (7)=(5)x(6)
1974	16,082	100	16,082	22,736	1.7716	40,279
1975	193,500	100	193,500	258,415	1.6105	416,177
1976	338,000	100	338,000	429,101	1.4641	628,247
1977	426,000	88	374,880	454,969	1.3310	605,564
1978	262,500	70	183,750	209,751	1.210	253,799
1979	305,526	50	152,763	164,831	1.10	181,314
1980	383,903	20	76,781	76,781	1.0	76,781
Totals	1,925,511		1,335,756	1,616,584		2,202,161

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[a] See text for source.

[b] Percentages are based on conversation with Diana Nyyssonen, January 26, 1981.

[c] Costs for salaries + overhead and costs for equipment + other items were separately estimated. Inflation factors from the U.S. Office of Personnel Management were applied to salaries + overhead. Inflation factors from the Bureau of Labor Statistics for "measuring and integrating instruments" were applied to the cost of equipment + other items.

[d] Single Compound Amount factors were selected for a 10 percent discount rate from the table in appendix B.

Photomask-related research expenditures adjusted for inflation amounted to $1,616,584.

4. Expenditures expressed in 1980 dollars were compounded at a rate of 10 percent per year to find their present (1980) value. The compounding was necessary to adjust for the opportunity cost of money--the net benefits that would have been realized if the money had been spent for something other than the linewidths measurement project. We used a compounding rate of 10 percent per year, which is the rate specified for federal use by the Office of Management and Budget.[1] Compounding is discussed in appendix B. After compounding, the present value of photomask-related linewidth expenditures in 1980 dollars (col. 7) amounted to about $2.2 million for the seven-year period.

Industry costs

There are other costs of developing the SRM and procedures which were not borne by NBS but may be considered costs of the research. These other costs were not quantified for this report. They include: (1) the costs incurred by firms to cooperate in two interlaboratory studies in the 1977-1980 period and (2) industry costs of loaning a number of linewidth measuring systems to NBS for use in its workshops.

Costs to individual firms of implementing NBS results were estimated in chapters 2 and 3 and are not included in research costs.

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[1] U.S. Office of Management and Budget, "Circular No. A-94 Revised," March 27, 1972.

6. CONCLUSIONS

Summary

This report has estimated the costs and benefits of using the NBS-developed Standard Reference Material 474 and related procedures for measuring linewidths on photomasks. We used a model to estimate the net benefits per mask for a hypothetical IC manufacturer with inhouse mask-making facilities. Steps in the analysis are summarized in table 6.1 at the end of this section.

For masks used in projection printing of wafers, benefits net of implementation costs were $179 per mask. However, NBS gets credit for only $82 of these benefits since presumably the industry would have eventually improved measurements on its own. For masks intended for contact printing of wafers, the benefits are $15 per mask, with NBS getting credit for $7.

Implications of the study

The results of applying the model to a particular case and the sensitivity analysis suggest that many companies are likely to realize substantial net benefits from improving their photomask linewidth measurements. Most combinations of values used in the model yielded positive net benefits and many benefits of improved photomask measurements were not quantified at all, so that actual benefits were probably understated.

However, the reader should be aware that the numbers estimated in this report are based on many assumptions which were not altered in the sensitivity analysis. Further study might show that some assumptions require modification in order to produce reliable upper- and lower-bound estimates of the cost savings.

A subjective impression, based on discussions with industry, is that industry managers consider the NBS photomask and wafer linewidth measurement research very important. They respect NBS as being a competent, impartial, authoritative source of measurement technology. However, some in industry feel that NBS research proceeds too slowly.

NBS linewidth measurement research has many impacts beyond the measurement of photomask linewidths. An extremely important example is the effects on measurement of linewidths on wafers. Many in industry believe that NBS impacts on wafer linewidths will be far more important than its effects on photomask linewidths. Including these other benefits would substantially increase the estimated economic benefits of NBS's research.

Uses of the model

NBS and industry can use models such as the one developed for this report in several ways.

1. NBS managers and researchers can use them to help estimate the overall benefits of NBS research, to help plan NBS research directions, to demonstrate benefits of improved measurement technology in terms meaningful

to corporate managers, and to help in deciding how to disseminate research results.

2. Company quality control managers can use such models to determine the payoff from investing in improved measurements and to demonstrate these payoffs to higher management. They can also use them to help choose among alternative strategies for investing in improved measurements. By doing a sensitivity analysis, companies can determine which statistics to collect to improve estimates of cost-savings.

Further research

This study has suggested several topics for further research:

1. Alter the assumptions in table 2.3, e.g., allow for random as well as systematic measurement error, additional measurements in the mask shop, and gradual improvements in yield as linewidths become closer to target value;

2. Analyze the benefits of improved measurements of linewidths on wafers;

3. Estimate industry-wide impacts of the photomask linewidth research and estimate impacts after there has been time for results to disseminate further in industry; and

4. Develop a guide for benefit-cost analysis of improved measurements for NBS managers. Such a guide would identify the general kinds of data needed for the analysis, suggest alternative methods of collecting this data, explain basic economic tools, and show how to determine aggregate benefits and costs. Worksheets could be included to help readers follow the method.

Economic research at NBS

In the past two years, the NBS Planning Office has funded two approaches to estimating benefits and costs of a NBS semiconductor research effort.

First, the approach used in this paper relies on a model of the acceptance measurement process. The model and the values used in illustrating it were based on discussions with NBS researchers and industry managers.

This approach helps in understanding how improved measurements benefit industry and lets NBS managers simulate effects of various types of measurement improvements under various conditions. This should be useful in planning directions for NBS measurement research and in showing individual companies how they may benefit from improved measurements, given their particular situation.

However, it can be very time consuming and difficult to develop such a model. For a heterogeneous industry, it can also be difficult to gather the data needed to apply the model for the various situations found in industry.

Also, aggregating may require hard-to-get data on diffusion of NBS results within companies and the mix of product sales.

Second, the Planning Office also funded a study, by Charles River Associates, of NBS impacts on productivity which included case studies of three NBS semiconductor research efforts. For the case studies, companies using NBS technology were surveyed by mail to directly obtain their estimates of dollar benefits.

This approach obtains inputs from a large number of companies at relatively low cost. Even if some responses are "guesstimates," they may be the best data available. This appears to be a less expensive way of getting dollar estimates than the modeling approach, and it may avoid the need to collect additional data for aggregating, since total reported effects can be used as a lower-bound estimate of aggregate effects and survey responses will automatically reflect a variety of situations.

A disadvantage of the survey approach is that, unless the questionnaire is very detailed, NBS may not know how companies arrived at their dollar estimates and it may not know just which aspects of improved measurements were responsible for the impacts.

Both of these approaches are likely to be useful to NBS in its future efforts to understand the economic effects of its research. A combination of the two approaches might be to develop a somewhat detailed model for estimating benefits and costs, and to use surveys to get data on steps in the measurement process as well as dollar benefits. This would help in evaluating the quality of the model and in interpreting company responses.

No matter which approach is used, there will be several problems in getting accurate information. For one, companies often do not know how improved measurements affect yields and other parameters. Also, it may be difficult for industry managers to trace particular technical advances to NBS, especially if NBS results have filtered out to industry over a long period. Companies may also be reluctant to reveal proprietary information, such as yield data.

However, because industry perceives NBS research as being quite useful, many companies are very willing to help by providing non-sensitive information for the benefit-cost analysis. This greatly aids NBS's ability to conduct studies of the economic impacts of its research.

Table 6.1 Summary of Steps in the Analysis

1. Determine values for all parameters listed in tables 3.1 and 3.2.
2. Determine the form of the probability density function f(x) describing mask linewidths.
3. Calculate the limits of integration for f(x) ($A1'_i$, $A2'_i$, $A1''_i$ and $A2''_i$) using table 2.2.
4. Calculate probabilities P_2' through P_6' and P_2'' through P_6'' using equations (5) and (6) in table 2.1.
5. Calculate costs of measurement error before and after improving procedures, using equations (3) and (4) in table 2.1.
6. Calculate implementation costs C4 for the "with NBS" situations using equation (7) in table 2.1.
7. Calculate implementation costs C4* for the "without NBS" situation using equation (8) in table 2.1.
8. Calculate benefits for the "with NBS" situation using equation (1) in table 2.1.
9. Recompute benefits for the "without NBS" situation using equation (2) in table 2.1.
10. Subtract the "without NBS" benefits from the "with NBS" benefits to find the benefits credited to the NBS research (equation [9] in table 2.1).

APPENDICES

A. GLOSSARY
B. DISCOUNTING TECHNIQUES
C. PUBLICATIONS RELATED TO NBS LINEWIDTH MEASUREMENT RESEARCH
D. SELECTED BIBLIOGRAPHY

APPENDIX A

GLOSSARY[1]

ACCEPTANCE MEASUREMENT - measurement of characteristics of incoming products to make sure they meet specifications.

ACCURACY - (in length metrology) closeness to the true length as defined by the national standard of length.

CALIBRATION CURVE - for linewidths, formula for correcting known systematic errors in linewidth measurements.

CHIP - see Die.

COMPOUNDING - increasing the value of a dollar amount to find its value at a later time. (This can be done using a Single Compound Amount factor.)

CONTACT PRINTING - printing masks or wafers from a photomask by placing the photomask in contact with the photoresist-coated surface to be exposed.

DEVICE - a unit containing a functionally complete integrated circuit pattern.

DIE - the portion of a wafer bearing an individual circuit or device. (One wafer has an array of such circuits.)

DISCOUNT RATE - the interest rate reflecting the time value of money that is used to convert benefits and costs occurring at different times to equivalent values at a common time.

DISCOUNTING - a technique for converting future cash flows to equivalent amounts at an earlier point in time.

INTEGRATED CIRCUIT (IC) - an interconnected group of circuit elements such as resistors and transistors on a single tiny chip of semiconductor material, where each chip comprises a complete operable electronic circuit.

LINE - a single feature of the pattern on a wafer or photomask.

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[1] In some cases the definitions given here are simplified and tailored to this report. For more generally applicable and exact definitions of engineering terms, see American National Standard ANSI/ASTM F 127-74, Standard Definitions of Terms Relating to Photomasking Technology for Microelectronics, and "Procedures for Using SRM 474," National Bureau of Standards, June 9, 1980, pp. A-4 through A-7. For standard definitions of economics terms, see Marshall, H.E.; Ruegg, R.T.; and Petersen, S.R., Recommended Practice for Measuring Life-Cycle Costs of Buildings and Building Systems, NBSIR 80-2040 (Washington, D.C.: National Bureau of Standards, 1980).

LINEWIDTH - the width of a line as measured between its two edges.

MARKET INTEREST RATES - interest rates actually paid by borrowers. Market rates generally include a premium to compensate for inflation.

MICROMETER (μm) - one millionth of a meter.

PHOTOMASK - a glass plate with a pattern used for exposing photoresist-coated wafers in the fabrication of integrated circuits (analogous to a transparency in a photographic process).

PHOTORESIST - a radiation-sensitive substance used to coat wafers in IC fabrication. Exposed and developed photoresist masks the wafer in a way useful for creating patterns on the substrate.

POLARITY - for a photomask, whether a line is opaque or transparent.

PRESENT VALUE - the value of a benefit or cost at the present time (i.e., as of the base period), found by discounting future cash flows or compounding past cash flows to the present.

PROJECTION PRINTING - printing wafers by projecting an optical image of the photomask on the photoresist-coated wafer.

RANDOM ERROR - in measurements, the component of measurement error which increases the spread of measured values about the mean, but does not affect the mean. (An increase in random error reduces measurement repeatability.)

REAL INTEREST RATE - the interest rate expressed in constant dollars, i.e., dollars which do not reflect price inflation. (If there is inflation, the real rate is less than the market rate.)

REPEATABILITY - a measure of the ability to make consistent measurements within a single organization.

RESIST - see photoresist.

SEMICONDUCTORS - materials which conduct electricity better than insulating materials but not as well as metals.

SINGLE PRESENT WORTH (SPW) FACTOR - a discount factor by which a value may be multiplied to find its value at an earlier point in time.

SINGLE COMPOUND AMOUNT (SCA) FACTOR - a factor by which a value may be multiplied to find its value at a later point in time.

STANDARD REFERENCE MATERIALS (SRMs) - physical calibration standards sold by the National Bureau of Standards. The SRM 474 and SRM 475 are coated glass plates with line patterns used in calibrating optical microscopes.

STEP AND REPEAT - a method for exposing photomasks and wafers which involves making an exposure and then stepping the image to the next position to create an identical pattern.

SYSTEMATIC ERROR - in measurement, the measurement bias; the difference between the true linewidth value and the limiting mean of the linewidth measurements. (The limiting mean is the mean which the sample mean approaches as the number of measurements increases.)

TARGET VALUE - for linewidths, the desired linewidth.

UNIFORM PRESENT WORTH (UPW) FACTOR - a discount factor for converting a series of recurring sums to their value at an earlier point in time.

WAFER - a crystal slice used in fabricating semiconductor devices.

WORKING PLATE - a photomask (usually made from a master or sub-master mask) used in wafer fabrication.

YIELD - the percent of product which meets acceptance standards during measurement and testing.

APPENDIX B. DISCOUNTING TECHNIQUES

This appendix explains how to discount or compound to accurately calculate the costs and benefits of research.

A one-dollar cost or benefit is worth less today if it will occur in the future than if it occurs in the present, even in the absence of inflation. This is because money received now can be invested at a profit which is lost if the money is not received until later. Similarly, a one-dollar cost or benefit is worth more if it occurred in the past than if it occurs in the present. Therefore, future dollar effects must be discounted (reduced) to find their present value, and past dollar effects must be compounded (increased) to find their present value.

A project which has zero net benefits (i.e., benefits equal costs) when all amounts are discounted at 10 percent is the equivalent of a project which returns 10 percent when evaluated without discounting. It is important to remember this when comparing projects.

In this report, for the purpose of discounting or compounding we assume that all amounts occur at the end of the year.

Compounding past sums

In table 5.1 in chapter 5, 1974 research costs were compounded to find their 1980 value. Original research expenditures were \$16,082. Adjusting for inflation increased the amount to \$22,736. This amount was then compounded at a rate of 10 percent over the six-year period through 1980, using the following formula:

$$\begin{aligned}\text{Present Value (1980)} &= \text{Original Sum X SCA} \\ &= \$22{,}736 \text{ X } 1.7716 \\ &= \$40{,}279\end{aligned}$$

The Single Compound Amount factor (SCA) was chosen from table B.1 in appendix B for a period of six years. All factors in table B.1 are for a 10 percent discount rate, but the SCA can be computed for other discount rates using the formula:

$$\text{SCA} = (1 + r)^t$$

where "r" is the discount rate and "t" is the number of years.

Discounting future sums

Equations (7) and (8) in table 2.1 discount future implementation costs to their present value. The equation for implementation costs is:

$$C4 = \frac{2}{kT}\,[C5+C6\ \underline{UPW_{(t-s)}} + \sum_{i=1}^{j} C7_i\ \underline{SPW_{u(i)}}]\ \underline{SPW_s}$$

The discount factors are underlined. The expression inside the brackets shows implementation costs discounted to the implementation year. The SPW_s factor further discounts from the implementation year "s" to the present. The discount factors are discussed some more below.

Uniform Present Worth (UPW)

Costs which are the same each year (C6) can be discounted using a Uniform Present Worth (UPW) factor for the number of years (t-s) over which the cost occurs. The UPW factor can be selected from table B.1 or computed using the following formula:

$$UPW = \frac{(1+r)^t - 1}{r(1+r)^t}$$

Single Present Worth (SPW)

Future costs which are not the same each year ($C7_i$) are each discounted using a Single Present Worth (SPW) factor for the year in which the cost occurs. The Single Present Worth factor can be selected from table B.1 or computed using the formula:

$$SPW = \frac{1}{(1+r)^t} \quad .$$

The entire expression inside the brackets is also discounted by a Single Present Worth factor. This is because if the implementation year is in the future (e.g., 1981 for a base year of 1980), costs must be further discounted to adjust for this delay.

An Example

For the values:

C5 = \$13,460 (initial cost)
C6 = \$6,600/year (equal annual costs for 5 years)
$C7_1$ = \$6,600 (2 years after implementation)
$C7_2$ = \$6,600 (4 years after implementation)
r = 10 percent (real discount rate)
kT = 50,000 (number of masks measured over five years)

Discounted costs C4 would be:

$$C4 = \frac{2}{50,000}\ [\$13,460+\$6,600(3.791)+\$6,600(.8264)+\$6,000(.6830)](.9091)$$

$$= \$1.76/\text{mask}$$

where:

3.791 is a UPW factor from table B.1 for a 5-year period
.8264 is a SPW factor from table B.1 for 2 years
.6830 is a SPW factor from table B.1 for 4 years
.9091 is a SPW factor from table B.1 for 1 year

Average benefits over analysis period

Benefits (C' - C") in equation (1) in table 2.1 are benefits/mask in a single year, e.g., 1980. However, these benefits are repeated over the period (t-s). For example, benefits of (C'-C") might occur each year for five years. To find the average benefits per mask over the analysis period, discounted to the implementation year, we multiply the one-year benefits (C'-C") by the factor $\frac{UPW_{(t-s)}}{T}$. This averages the higher per-mask benefits of earlier years with the lower per-mask benefits of later years (benefits of later years are lower due to discounting). The following section explains how $\frac{UPW_{(t-s)}}{T}$ was obtained.

The benefits per mask in the year after the procedures are implemented are (C'-C") x SPW_1, where (C'-C") is the per-mask benefits before discounting and SPW_1 is the Single Present Worth discounting factor for one year. The benefits per mask in the second year are (C'-C") x SPW_2, and so on. Assuming masks are produced at a constant rate over the analysis period, average benefits per mask are:

$$\frac{(C'-C") \times SPW_1 + (C'-C") \times SPW_2 + \ldots + (C'-C") \times SPW_{(t-s)}}{T} \tag{13}$$

$$= \frac{(C'-C")\ UPW_{(t-s)}}{T} \tag{14}$$

where T is the analysis period, (t-s) is the period over which benefits occur and UPW is the Uniform Present Worth factor. UPW can be found in table B.1 in appendix B, or calculated from the formula in appendix B, for time period (t-s).

APPENDIX B

Table B.1 Discounting Factors for 10 Percent Discount Rate

n 1	Compound amount factor SCA 2	Present worth factor SPW 3	Sinking fund factor USF 4	Capital recovery factor UCR 5	Compound amount factor UCA 6	Present worth factor UPW 7.	n
1	1.1000	0.9091	1.00000	1.10000	1.000	0.909	1
2	1.2100	0.8264	0.47619	0.57619	2.100	1.736	2
3	1.3310	0.7513	0.30211	0.40211	3.310	2.487	3
4	1.4641	0.6830	0.21547	0.31547	4.641	3.170	4
5	1.6105	0.6209	0.16380	0.26380	6.105	3.791	5
6	1.7716	0.5645	0.12961	0.22961	7.716	4.355	6
7	1.9487	0.5132	0.10541	0.20541	9.487	4.868	7
8	2.1436	0.4665	0.08744	0.18744	11.436	5.335	8
9	2.3579	0.4241	0.07364	0.17364	13.579	5.759	9
10	2.5937	0.3855	0.06275	0.16275	15.937	6.144	10
11	2.8531	0.3505	0.05396	0.15396	18.531	6.495	11
12	3.1384	0.3186	0.04676	0.14676	21.384	6.814	12
13	3.4523	0.2897	0.04078	0.14078	24.523	7.103	13
14	3.7975	0.2633	0.03575	0.13575	27.975	7.367	14
15	4.1772	0.2394	0.03147	0.13147	31.772	7.606	15
16	4.5950	0.2176	0.02782	0.12782	35.950	7.824	16
17	5.0545	0.1978	0.02466	0.12466	40.545	8.022	17
18	5.5599	0.1799	0.02193	0.12193	45.599	8.201	18
19	6.1159	0.1635	0.01955	0.11955	51.159	8.365	19
20	6.7275	0.1486	0.01746	0.11746	57.275	8.514	20
21	7.4002	0.1351	0.01562	0.11562	64.002	8.649	21
22	8.1403	0.1228	0.01401	0.11401	71.403	8.772	22
23	8.9543	0.1117	0.01257	0.11257	79.543	8.883	23
24	9.8497	0.1015	0.01130	0.11130	88.497	8.985	24
25	10.8347	0.0923	0.1017	0.11017	98.347	9.077	25
26	11.9182	0.0839	0.00916	0.10916	109.182	9.161	26
27	13.1100	0.0763	0.00826	0.10826	121.100	9.237	27
28	14.4210	0.0693	0.00745	0.10745	134.210	9.307	28
29	15.8631	0.0630	0.00673	0.10673	148.631	9.370	29
30	17.4494	0.0573	0.00609	0.10608	164.494	9.427	30
31	19.1943	0.0521	0.00550	0.10550	181.943	9.479	31
32	21.1138	0.0474	0.00497	0.10497	201.138	9.526	32
33	23.2252	0.0431	0.00450	0.10450	222.252	9.569	33
34	25.5477	0.0391	0.00407	0.10407	245.477	9.609	34
35	28.1024	0.0356	0.03369	0.10369	271.024	9.644	35
40	45.2593	0.0221	0.00226	0.10226	442.593	9.779	40
45	72.8905	0.0137	0.00139	0.10139	718.905	9.863	45
50	117.3909	0.0085	0.00086	0.10086	1163.909	9.915	50
55	189.0591	0.0053	0.00053	0.10053	1880.591	9.947	55
60	304.4816	0.0033	0.00033	0.10033	3034.816	9.967	60
65	490.3707	0.0020	0.00020	0.10020	4893.707	9.980	65
70	789.7470	0.0013	0.00013	0.10013	7887.470	9.987	70
75	1271.8952	0.0008	0.00008	0.10008	12708.954	9.992	75
80	2048.4002	0.0005	0.00005	0.10005	20474.002	9.995	80
85	3298.9690	0.0003	0.00003	0.10003	32979.690	9.997	85
90	5313.0226	0.0002	0.00002	0.10002	53120.226	9.998	90
95	8556.6760	0.0001	0.00001	0.10001	85556.760	9.999	95
100	13780.6123	0.0001	0.00001	0.10001	137796.123	9.999	100

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Accurate dimensional measurements are vital to quality control in the semiconductor industry. This paper presents a method for estimating the dollar cost-savings from improving integrated-circuit photomask linewidth measurements. The method is illustrated with a case study of a hypothetical semiconductor device manufacturer who uses a Standard Reference Material (SRM) developed at the National Bureau of Standards for optical microscope calibration.

Benefits of investing in improved photomask linewidth measurements include reducing disputes between mask maker and mask customer, reducing waste of good photomasks, and increasing device yields. For the hypothetical manufacturer described in the study, these benefits were much greater than costs of implementing the new measurement procedures.

While the model is tailored to photomask linewidth measurements, its concepts can be applied to many other types of measurements.

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