

SEMI M56-1103

PRACTICE FOR DETERMINING COST COMPONENTS FOR METROLOGY EQUIPMENT DUE TO MEASUREMENT VARIABILITY AND BIAS

This practice was technically approved by the Global Silicon Wafer Committee and is the direct responsibility of the North American Silicon Wafer Committee. Current edition approved by the North American Regional Standards Committee on September 3, 2003. Initially available at www.semi.org October 2003; to be published November 2003.

1 Purpose

1.1 In silicon manufacturing product disposition is typically contingent on metrology equipment output. For example, a piece of work may be shipped, scrapped, or reworked based on information from one or more measured output characteristics. A cost model provides a mechanism for estimating the costs associated with operating metrology equipment under certain sets of assumptions and conditions.

1.2 This practice provides a standard methodology for metrology equipment suppliers and users to determine the cost due to misclassification of product because of measurement variability and bias during testing of the product for conformance to a specification.

1.3 This practice is intended to be useful for pre-purchase evaluation of measurement equipment with different P/T (Precision/Tolerance) ratios. It is also intended to be useful when comparing the operation of a single measurement instrument in different throughput modes where P/T ratio changes with the throughput mode utilized or other equipment setup factors. This practice can help users select the optimum cost solution based on their specific process capability and requirements.

1.4 Neither traditional cost elements (e.g., equipment, maintenance, operational, and staffing cost) nor product cost data are included in the practice; it is intended that each user should utilize appropriate data based on the applicable business model for the facility.

2 Scope

2.1 This practice covers a methodology to determine the costs associated with misclassification of product due to variability and bias of measurement equipment. These costs are associated with failing product that conforms with specifications and passing product that does not conform with specifications.

2.2 This practice can be applied to make relative cost comparisons between two or more measurement gauges operating under conditions specified by the user. These conditions may include any aspects of the measurement system affecting the measurement results directly or

indirectly (e.g., ambient conditions, throughput, recipe). This practice can also be used to compare the relative costs of a single instrument under different operating conditions.

2.2.1 A measurement gauge is defined by a specific realization of systems and subsystems required to make measurements. Gauges that differ in at least one system or subsystem may be considered different for the purpose of comparison.

2.3 This practice can be applied to any metrology equipment or to the metrology portion of any equipment that includes metrology.

2.4 This practice covers the case in which the metrology equipment is used to make binary decisions about the item being measured, that is, only two outcomes are possible (e.g., pass/fail, go/no-go, ship/scraper). Models for decisions with more than two outcomes, such as the binning of data, are beyond the scope of this practice.

2.5 To apply the formulae in this practice, the user must estimate either the probability density function (PDF) or cumulative distribution function (CDF) of the process characteristic or characteristics of interest. The distributions can be based on a theoretical model or on empirical information obtained from manufacturing data.

2.6 To apply the formulae in this practice, the user must be able to estimate all biases and variances associated with the equipment being compared under the specified operating conditions and with respect to the process characteristic(s) of interest. These values can be obtained from a measurement system capability analysis (see SEMI E89).

2.7 To apply the methodology of this practice, the user must estimate the costs of classification and misclassification due to decisions made as a result of measurements. Estimates of such costs are obtained from the business model used to describe the manufacturing process in which the measurements are performed. Consequently, different users may arrive at different estimates of costs because their computations may contain different elements.

2.8 The output of this practice is the cost component due to measurement variability and bias for each process characteristic and metrology system evaluated.

2.9 This practice does not consider costs associated with other components of uncertainty outside of measurement variability and bias.

2.10 Although it is focused on the issue of misclassification, the practice may be extended to include costs associated with correct classification by the metrology equipment.

2.11 This practice was developed to evaluate metrology equipment used in silicon wafer manufacturing, but it may be extended to other types of metrology equipment by making suitable modifications.

NOTICE: This practice does not purport to address safety issues, if any, associated with its use. It is the responsibility of the users of this standard to establish appropriate safety health practices and determine the applicability of regulatory or other limitations prior to use.

3 Limitations

3.1 Application of this practice requires that all measurement variances and biases, process characteristic distributions, and costs of classification and misclassification be accurately characterized. If this is not done, the resulting calculation may be in error.

3.2 Application of this practice also requires that measurement variances and biases be constant over the measurement range interval of interest. If this is not the case, the resulting calculation may be in error.

3.3 This practice considers only the case of two convolved distributions, process characteristic variability and measurement variability; consideration of additional distributions (such as would be required if the measurement bias or variance were assumed to be a function of the measured value) is beyond the scope of this practice.

3.4 Extension of the model to the cases of decisions based on (1) measurements on multiple gauges, (2) multiple inspections with the same gauge or (3) on multiple characteristics is outside the scope of this practice, but information on such extensions is provided in Related Information 1 for the convenience of the user.

3.5 This model should not be confused with a cost-of-ownership model, such as that developed in SEMI E35, which explicitly includes information on the cost elements involved.

4 Referenced Standards

4.1 SEMI Standards

SEMI E35 — Cost of Ownership for Semiconductor Manufacturing Equipment Metrics

SEMI E89 — Guide for Measurement System Capability Analysis

SEMI M1 — Specifications for Polished Monocrystalline Silicon Wafers

SEMI M27 — Practice for Determining the Precision over Tolerance Ratio of Test Equipment

4.2 ISO Document¹

International Vocabulary of Basic and General Terms in Metrology, Second Edition [VIM]

NOTICE: Unless otherwise indicated, all documents cited shall be the latest published versions.

5 Terminology

5.1 General terminology related to metrology is defined in VIM.

5.2 Terminology relating to measurement system capability analysis is defined in SEMI E89.

5.3 Terminology related to silicon wafer technology is defined in SEMI M1.

5.4 Other Definitions

5.4.1 *alpha error* — the error that occurs when a conforming item is incorrectly reported as non-conforming. This is also called Type I error.

5.4.2 *alpha probability*, α — the probability of an alpha error, also called the alpha error rate.

5.4.3 *beta error* — the error that occurs when a non-conforming item is incorrectly reported as conforming. This is also called Type II error.

5.4.4 *beta probability*, β — the probability of a beta error, also called the beta error rate.

5.4.5 *bias*, δ — the difference between the mean value of measurements made on the same object and a true value.

NOTE 1: Bias is illustrated in Related Information 2 (Figure R2-1). However, in many cases the true value is unknown. A value established by reference gauges or a consensus value may be used as a substitute.

¹ International Organization for Standardization: ISO Central Secretariat, 1, rue de Varembé, Case postale 56, CH-1211 Geneva 20, Switzerland, Telephone: 41.22.749.01.11; Fax: 41.22.733.34.30, Web site: www.iso.ch.

5.4.6 *cumulative distribution function (CDF)* — a mathematical formula that describes the probability a measurable event occurs at or below a specific value.

5.4.7 *distribution* — a characterization of the probability of realization for a measurable event over the range of values that the measurements may assume.

5.4.8 *joint probability* — a probability density or cumulative distribution function comprised of two or more random variables.

5.4.9 *lower specification limit (LSL)* — value of a characteristic below which a product is said to be non-conforming.

5.4.10 *measurand* — particular attribute of a phenomenon, body, or substance subject to measurement [VIM].

5.4.11 *measurement variability* — differences associated with making multiple measurements on a given measurand under specific conditions.

NOTE 2: Measurement variability (its distribution) is illustrated in Related Information 2 (Figure R2-1). Common (general) estimators of measurement variability are the variance, standard deviation, and variance components. Specific estimators include repeatability and reproducibility.

5.4.12 *probability density function (PDF)* — a mathematical formula that specifies the relationship between values that a random variable may assume and their likelihood of occurrence. It is the first derivative of the CDF.

5.4.13 *random variable* — a measurable event occurring such that any value from its distribution is equally likely to take place.

5.4.14 *standard deviation, σ* — the positive square root of the variance.

NOTE 3: The standard deviation of a population may be estimated from experimentally obtained data by the sample standard deviation (s):

$$s = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2}$$

where:

n = number of data values,

x_i = value of the i^{th} data point, and

$\bar{x}$ = mean of the data distribution.

5.4.15 *upper specification limit (USL)* — value of a characteristic, above which a product is said to be non-conforming.

5.4.16 *variance* — a statistical estimator that quantifies spread around the mean of a PDF.

6 Summary of Practice

6.1 The process distribution for the characteristic of interest is estimated or determined.

6.2 The bias and standard deviation for the characteristic of interest are determined for each measurement instrument to be evaluated or compared.

6.3 The quantities α and β are calculated from the appropriate formula depending on the nature of the specification (LSL only, USL only, or both).

6.4 Costs, based on the applicable business model, are assigned to each of the four possible measurement outcomes.

6.5 The cost components arising from measurement variability are calculated for each measurement instrument being evaluated or compared.

6.6 The costs due to measurement variability are compared to establish the most cost effective measurement solution for the application.

7 Procedure

7.1 Estimate the PDF for the process characteristic to be studied. This can be done using empirical data that represents the process. Although actual data may be used to create a discrete PDF, it is sometimes convenient to use the data to parametrically fit a PDF model (e.g., log normal).

7.2 Unless already known, establish the bias and standard deviation for each measurement gauge to be compared in accordance with SEMI E89.

7.3 In all cases take the measurement influence into account so that it does not broaden the PDF. This may be done by taking repeated measurements at each point in the measurement range and calculating the mean, or by deconvolving the process characteristic PDF, $f(x)$, and the measurement variability CDF, $G(u)$, generally assumed to be a Gaussian (or normal) distribution with arithmetic mean equal to the bias, so that:

$$G(u) = \Phi(u) = \int_{-\infty}^u \frac{1}{\sqrt{2\pi}\sigma_M} \exp\left[-\frac{(x-\delta)^2}{2\sigma_M^2}\right] dx \quad (1)$$

where:

δ = bias,

σ_M = standard deviation of the measurement distribution.

NOTE 4: The quantity σ_M includes the effects of the change in bias over the time interval in which σ_M has been established.

7.4 Calculate α and β as follows (Note 4). Note that the symbols in the equations for α and β have the following meanings:

$f(x)$ = PDF of process characteristic x ,

USL = upper specification limit,

LSL = lower specification limit, and

$\Phi(u)$ = Gaussian CDF (see Equation (1) in Section 7.3).

7.4.1 For a characteristic with only a USL, use the following equations to calculate α and β :

$$\alpha = \int_{-\infty}^{USL} \left[1 - \Phi \left(\frac{USL - x + \delta}{\sigma_M} \right) \right] f(x) dx$$

$$\beta = \int_{USL}^{\infty} \left[\Phi \left(\frac{USL - x + \delta}{\sigma_M} \right) \right] f(x) dx$$

7.4.2 For a characteristic with only an LSL, use the following equations to calculate α and β :

$$\alpha = \int_{LSL}^{\infty} \left[\Phi \left(\frac{LSL - x + \delta}{\sigma_M} \right) \right] f(x) dx$$

$$\beta = \int_{-\infty}^{LSL} \left[1 - \Phi \left(\frac{LSL - x + \delta}{\sigma_M} \right) \right] f(x) dx$$

7.4.3 For a characteristic with both upper and lower specifications limits, use the following equations to calculate α and β :

$$\alpha = \int_{LSL}^{USL} \left[1 - \Phi \left(\frac{USL - x + \delta}{\sigma_M} \right) \right] f(x) dx + \int_{LSL}^{USL} \left[\Phi \left(\frac{LSL - x + \delta}{\sigma_M} \right) \right] f(x) dx$$

$$\beta = \int_{-\infty}^{LSL} \left[\Phi \left(\frac{USL - x + \delta}{\sigma_M} \right) - \Phi \left(\frac{LSL - x + \delta}{\sigma_M} \right) \right] f(x) dx + \int_{USL}^{\infty} \left[\Phi \left(\frac{USL - x + \delta}{\sigma_M} \right) - \Phi \left(\frac{LSL - x + \delta}{\sigma_M} \right) \right] f(x) dx$$

NOTE 5: Background information related to the calculation of α and β is given in Related Information 3.

7.5 Use a binary decision model. If measurement-based decisions are labeled as pass or fail and items are

inherently conforming or nonconforming, there are only four outcomes:

- pass a conforming item,
- fail a conforming item (α error),
- pass a nonconforming item (β error), and
- fail a nonconforming item.

The probabilities associated with these outcomes are $1-\alpha$, α , β , and $1-\beta$, respectively.

7.6 To define the cost model, assign costs to each of the four decisions above on the basis of the business model used for the manufacturing process as follows:

- c_{pc} : cost of passing a conforming item,
- c_{fc} : cost of failing a conforming item (α error),
- c_{pn} : cost of passing a non-conforming item (β error), and
- c_{fn} : cost of failing a non-conforming item.

7.6.1 Assign zero incremental cost to the two correct outcomes (c_{pc} and c_{fn}).

7.6.2 Assign the incremental costs for the error outcomes, c_{fc} and c_{pn} , on the basis of the business model used for the manufacturing process.

7.7 Calculate the cost due to misclassification resulting from measurement variability based on the assigned incremental costs given in Section 7.6 and the frequency of occurrence of α and β errors as follows:

$$\text{cost} = c_{fc}\alpha + c_{pn}\beta, \quad (2)$$

using the appropriate equations for α and β as given in Section 7.4, depending on the nature of the specification (LSL only, USL only, or both).

NOTE 6: See Related Information 4 for an example of this calculation.

7.8 If it is desired to include costs for correct as well as incorrect classification, calculate the total cost resulting from measurement variability based on the assigned incremental costs given in Section 7.6 and the frequency of occurrence of α and β errors as follows:

$$\text{cost} = c_{pc}(1-\alpha) + c_{fc}\alpha + c_{pn}\beta + c_{fn}(1-\beta), \quad (3)$$

using the appropriate equations for α and β as given in Section 7.4, depending on the nature of the specification (LSL only, USL only, or both).