

IEEE SW Test Workshop

Semiconductor Wafer Test Workshop

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Applied Metrology and Tool Gauge Studies

Tutorial Outline

- Introduction to Applied Metrology and Measurement System Analysis
- Case studies of metrology tool capability assessments and correlation comparisons
- Case studies of wafer sort floor problems and the metrology used to fix them

Introduction

- All manufacturing processes are a collection of measurable parameters that define success or failure
- Metrology is the science of using tools to measure those parameters
- Probe technologists are in the business of balancing test cell throughput, product yield, and product quality in a high-volume manufacturing environment
- They're surrounded by test cells and other metrology systems that generate an incredible amount of data

Introduction (cont.)

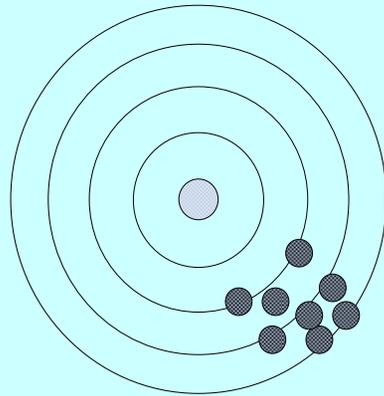
- Metrology tool selection, integration, and comparison with baseline performance expectations is almost an everyday occurrence
- It's imperative that probe technologists understand the capabilities and limitations of their metrology
 - Which metrology tool is the best for me?
 - How do I know if it's good enough?
 - How often do I need to test and calibrate it?
 - Why can't I get the same results from more than one tool?
 - What if the tool I have isn't good enough for the application I have for it?

Metrology: *What's Important?*

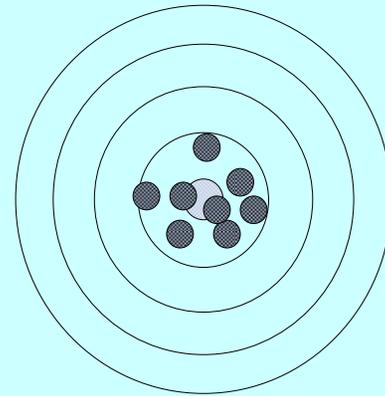
- Accuracy – how close a measurement value is to the ‘real’ or true value. Also called bias.
- Precision – how close multiple measurements are to each other under the same test conditions. Sometimes described as the combination of repeatability and reproducibility
- Repeatability – the capability to get the same test result every measurement when nothing in the test setup has changed (same conditions)
- Reproducibility – the ability to get the same test result when something has changed in the test setup (different conditions)

Accuracy versus Precision

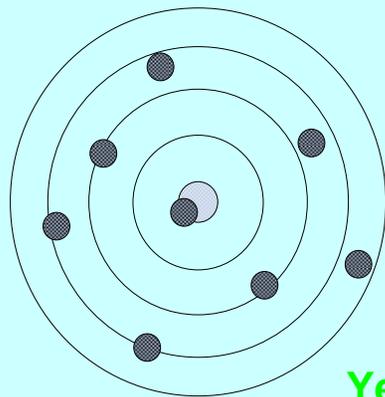
Specify whether each process is accurate and precise.



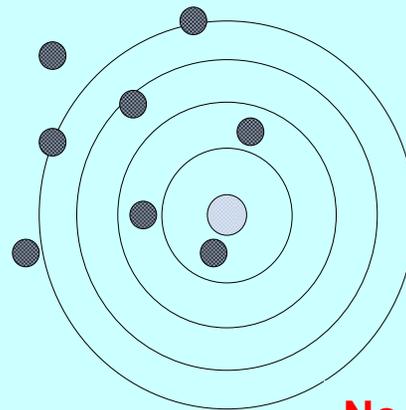
Accurate: _____ **No**
Precise: _____ **Yes**



Accurate: _____ **Yes**
Precise: _____ **Yes**



Accurate: _____ **Yes**
Precise: _____ **No**



Accurate: _____ **No**
Precise: _____ **No**

Metrology: *What Else?*

- Stability – the measurement result is the same over time (time-independent)
- Linearity – the precision and accuracy of the tool is the same across the full measurement range of the tool
- Speed – tool precision and measurement speed are almost always one attained at the expense of the other
- Discrimination – the capability of the tool to identify a small change in multiple measured values
- Cost – more expensive does not necessarily mean a better tool

Types of Metrology

- Certified-accurate
 - Measurement tools that are traced to reference standards through an unbroken chain of comparisons
 - National Institute of Standards and Technology (NIST)
- Comparative Metrology “Golden Reference”
 - Compare measurements against a golden reference or part that is not traced to a known calibrated standard
 - Comparative metrology lasts as long as the golden reference remains unchanged
- Process Monitoring
 - Measured values are compared to historical data
 - Accuracy of measurements is not as important as verifying process parameters are still within specified process window

Anatomy of a Metrology Tool

- The most basic requirements of a metrology tool to meet a particular measurement need are based on two fundamental tool characteristics
 - The uncertainty or variability in the measurement
 - The difference between the measurement result and the 'true value'
- The uncertainty of the measurement is a combination of variance components from random sources and from non-random or systematic sources
- The difference between the average of multiple measurements and the true or reference value is defined as the accuracy or bias of the metrology system

Uncertainty and Bias Defined

- So uncertainty is equal to random and systematic variation -

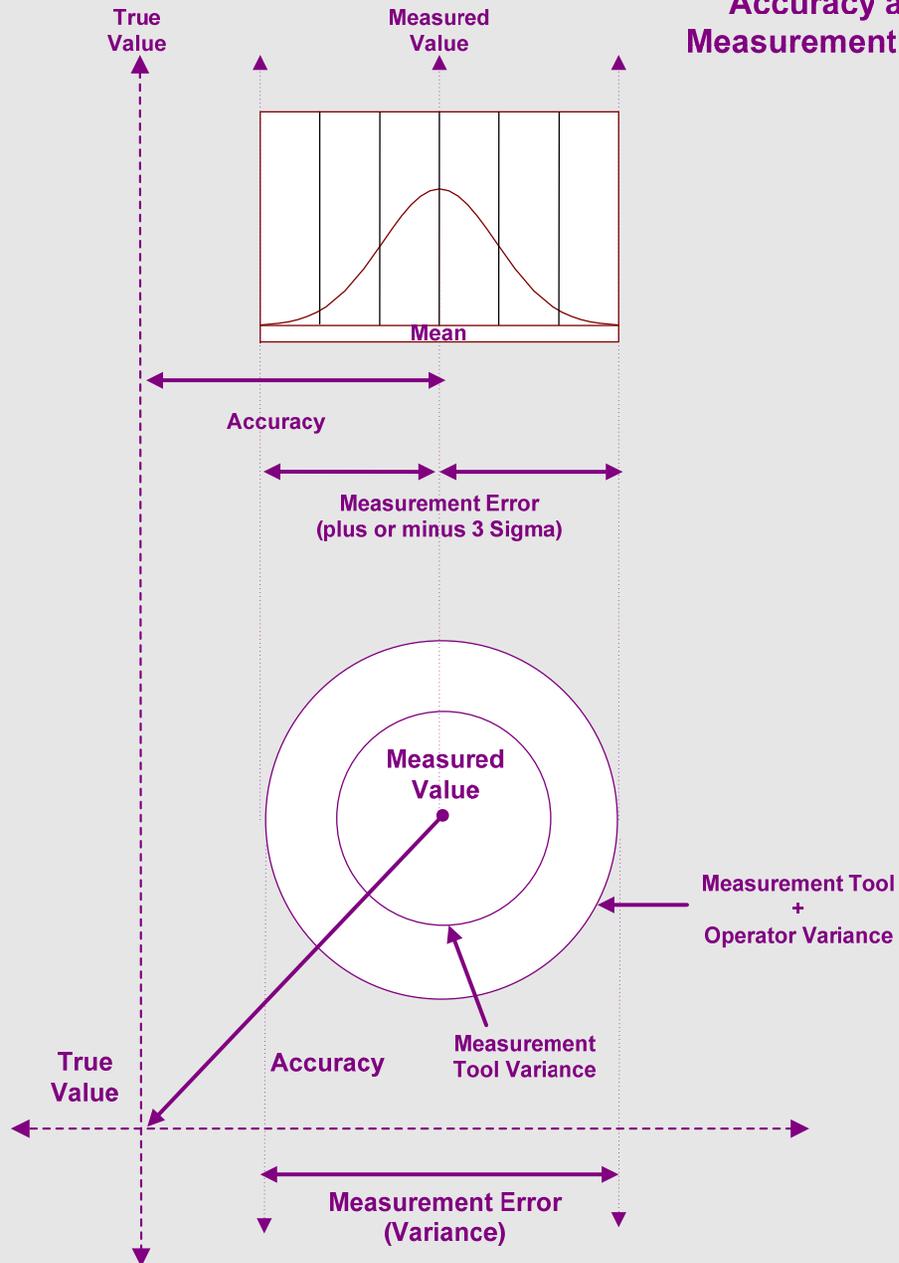
or

$$\sigma_T = \sigma_{av} + \sigma_{ev}$$

Where the *av* term is the appraiser or operator variance, and *ev* is the measurement tool variance.

- And bias is the difference between the measured value and the true value that can be minimized through a calibration process where the measurement tool results are compared to a reference value

Metrology Accuracy and Measurement Error



Measurement System Analysis

Measurement System Analysis (MSA)

The evaluation of the statistical properties
of repeatability, reproducibility, bias,
stability, and linearity

Gage Repeatability and Reproducibility (GRR)

A study of the variability
of the measurement system +
surrounding process

Accuracy Studies

Quantify the bias, stability, and
linearity of the measurement
system

Gage R&R Models

- **Crossed model.** A crossed model implies that each appraiser measured the same parts, which is true for classical gauge studies. A crossed model will give variance components for the following: Tool Operator, Measured Part, Operator*Part interaction and Measurement Error.
- **Nested model.** A nested model implies that each appraiser measured different parts. This would still be considered a valid gage study design but is not as common as the crossed design. A nested model will give variance components for the following: Tool Operator, Measured Part, Operator*Part interaction and Measurement Error.
- **Main Effect model.** A main effects model implies that measured parts are neither crossed or nested within operator, and could be considered a mixture of both. Any interaction error will be included as part of overall measurement error of the model. A main effect model will give variance components for the following: Operator, Measured Part, and Measurement Error.

Sample Size Considerations

- Measurement processes can include several variance components but typically include these;
 - One or more operators (k)
 - One or more parts to be measured (p)
 - Time (or repetitions (r))
- In classical gauge studies sample size is designed to ensure that $p*k*r > 30$ but the assumption is that your measurement data is normally distributed about the average measured value – something that depends on the item being measured
- If dealing with non-normally distributed measurement results it's recommended you consult a statistician

Calibration Frequency

- In general - tool bias needs to be reduced when the magnitude of the bias is large when compared to the precision of the system. This is normally a function of time or production units.
- There are several methods to determine the frequency of calibration
 - Tool manufacturer recommendation
 - Empirically-derived
 - Product or process specification requirements
- In an empirically-derived calibration frequency the tool is calibrated and then over time periodically tested against a reference until some undesired level of bias is achieved.

Speed versus Precision

- Often a measurement tool can be programmed to make measurements faster with some loss of precision or more slowly and gain more precision.
- Some tools have the ability to make multiple measurements and then report the *average* of the many measurements. This method can be used to reduce the variance intrinsic to the measurement tool; but at the expense of measurement speed.
- Some metrology systems have mechanical or electronic interlocks for equipment or personnel safety that inherently slow down system operation. Extreme caution should be used when changing these system settings. If in doubt consult your metrology system supplier.
- Gauge studies can be used to the relationship between speed vesus precision for optimize system performance.

Tool Capability and Your Specs

- Remember that the total uncertainty in a tool is a combination of the operating process of the tool (av) and the uncertainty in the tool itself (ev).
- One simple way to compare tool capability to a process specification is called the performance-to-tolerance ratio (P/T).
 - Ideally your P/T ratio would be 10% or less than your specification window
 - But it could be as much as 30% before the capability of the tool to monitor this process successfully is questioned
 - The critical nature of the process being monitored must be considered as well

$$\sigma_{R\&R} = \sigma_{av} + \sigma_{ev}$$

or

$$S_{R\&R} = \sqrt{S_{av}^2 + S_{ev}^2}$$

$$PT = \frac{6 \cdot S_{R\&R}}{USL - LSL} \cdot 100\%$$

Tool Correlation

- Two calibrated and similarly precise metrology tools will always have a lack of precision or correlation with each other that is greater than the precision of each tool.

$$\sigma_{T_{12}} = \sigma_{T_1} + \sigma_{T_2}$$

- Bias will also cause differences between similar tools.
- In situations where multiple metrology systems are being compared to each other often a third reference system or other standard is used as a comparative reference

Key References

- *Guide to the Expression of Uncertainty in Measurement*, (GUM) ISO Technical Advisory Group 4, Work Group 3, 1993
- *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*, National Institute of Standards and Technology Technical Note 1297, B. N. Taylor, and C. E. Kuyatt
- *ASTM Standards on Precision and Accuracy for Various Applications*, American Society for Testing and Materials, (ASTM), 1997

Key References

- *International Vocabulary of Basic and General Terms in Metrology*, (VIM) ISO TAG 4, WG1, 1993