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Pursuit of Perfection:
Metrology & Yield for Semiconductor Fabrication

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IEEE/EPS | 31 Oct. 2024

Overview

- What is yield?
- Who cares?
- Apple’s Yield Bounty
- Process Control is king
- Beating the System
- One Man’s Trash
- Measure twice, cut once
- Review

What is yield?

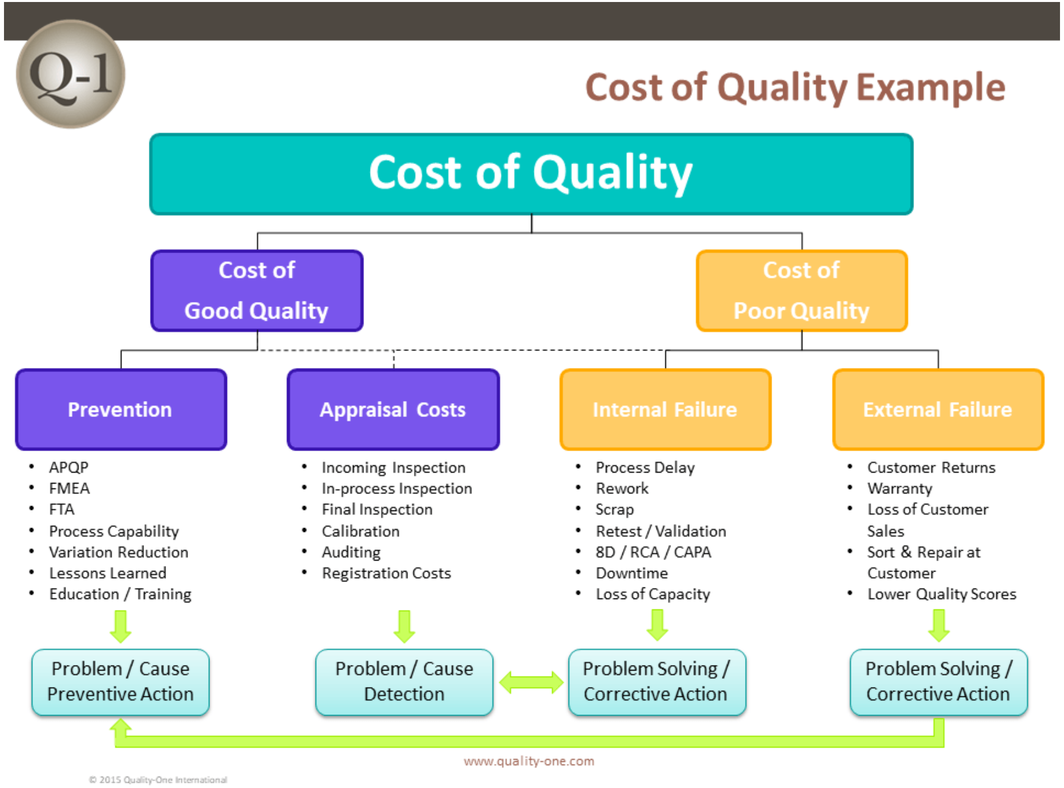
- Yield refers to the percentage successfully manufactured devices coming out of a manufacturing process
- Manufacturers try to increase yield, effectively reducing the price of a final product

Percent Yield

$$\% \text{Yield} = \frac{\text{Actual Yield}}{\text{Theoretical Yield}} \times 100\%$$

Who cares?

- ~~Time is money~~
- Money is money
- CoGQ << CoPQ
- Managers, quality engineers, and ultimately every employee should care (Bonuses, salary, etc)
- This is a really strong metric to determine whether you're at a "good" company!



Q-1

Cost of Quality Example

Cost of Quality

Cost of Good Quality

Prevention

- APQP
- FMEA
- FTA
- Process Capability
- Variation Reduction
- Lessons Learned
- Education / Training

Problem / Cause Preventive Action

Appraisal Costs

- Incoming Inspection
- In-process Inspection
- Final Inspection
- Calibration
- Auditing
- Registration Costs

Problem / Cause Detection

Cost of Poor Quality

Internal Failure

- Process Delay
- Rework
- Scrap
- Retest / Validation
- 8D / RCA / CAPA
- Downtime
- Loss of Capacity

Problem Solving / Corrective Action

External Failure

- Customer Returns
- Warranty
- Loss of Customer Sales
- Sort & Repair at Customer
- Lower Quality Scores

Problem Solving / Corrective Action

www.quality-one.com

Apple’s Yield Bounty

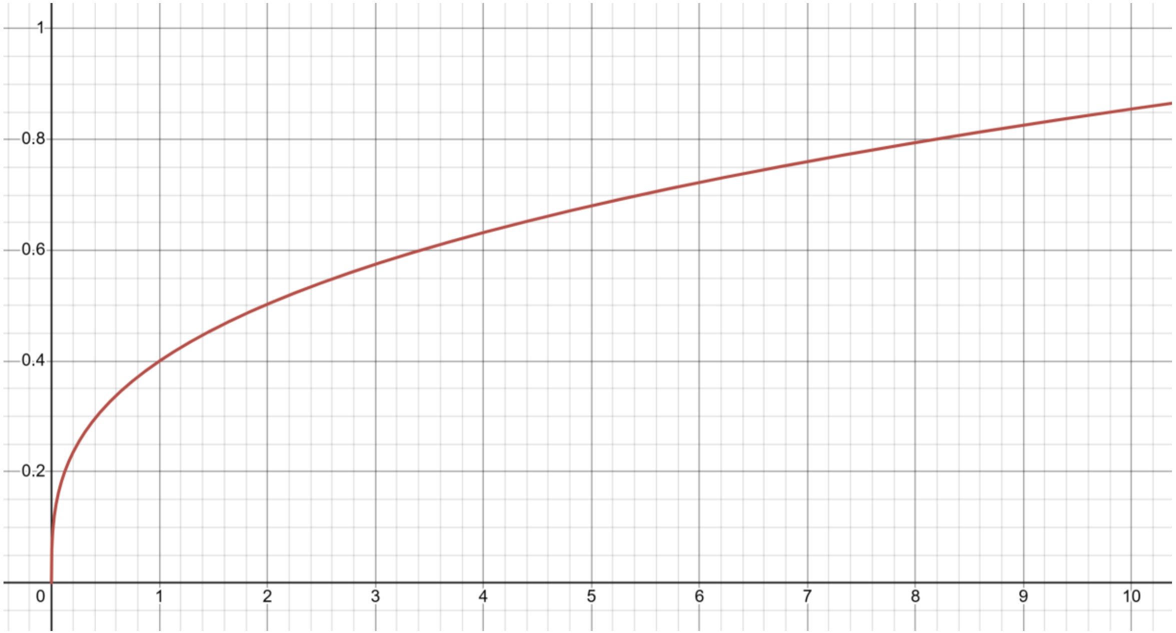
- TSMC typically charges ~$20k per wafer produced at 3nm node, regardless of yield (This becomes the customer’s problem)
- 200 dies per wafer -> $100/die (Assumed cost)
- Early-stage yield ~55%
- What is the new, real cost per die?

Apple's Yield Bounty

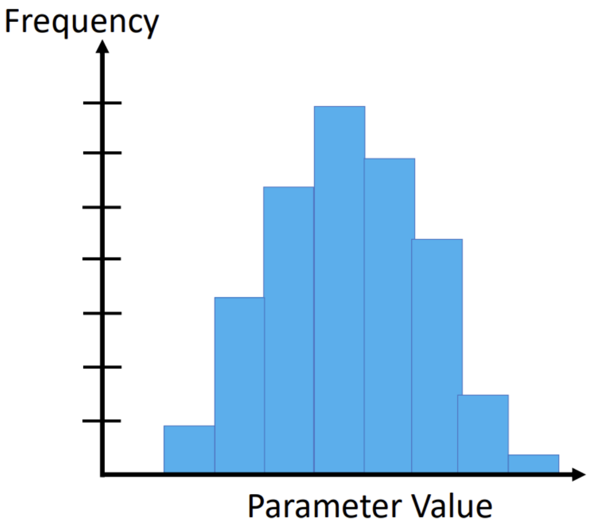
- Apple buys ALL of TSMC's production capability (3nm)… AND have really good lawyers
- TSMC, scared of losing ~75B/yr deal, agreed to sell KGD, until yield could be improved
- Apple removed risk in their product cost, simply because they're big enough to force their supplier into submission
- Deal stood until TSMC reached ~70% yield, before returning to wafer price model

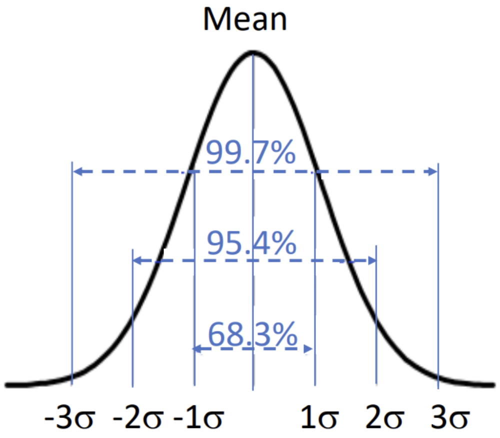
Apple’s Yield Bounty

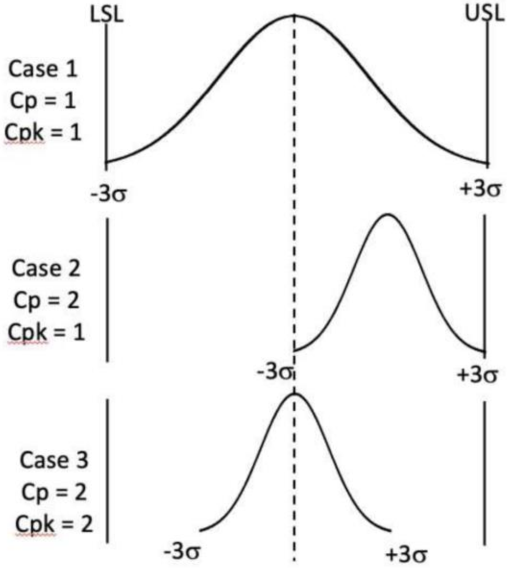
- Yield generally improves over time
- ~90% for mature processes
- ~50% for new processes
- Time, effort required to enable this improvement
- Diminishing returns???



Process Control is King!



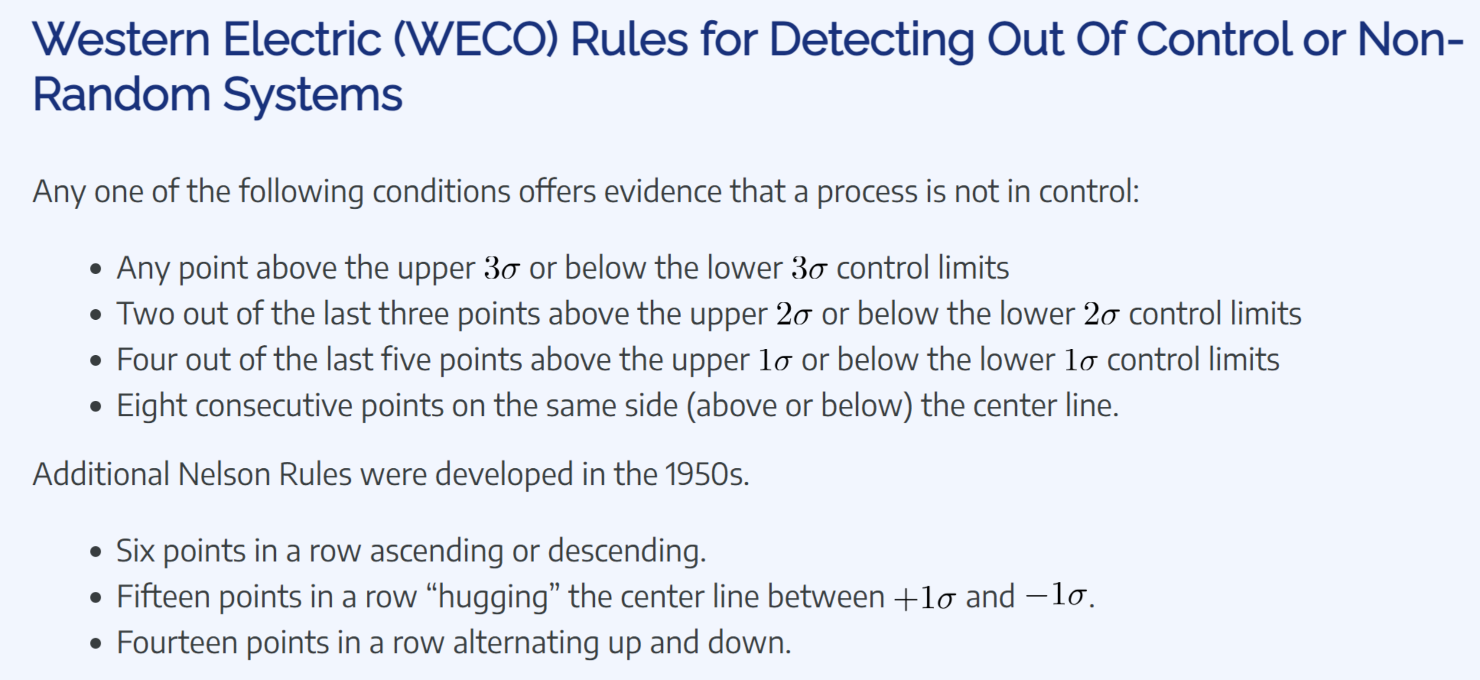




$$Cp = \frac{USL - LSL}{6\sigma} \qquad (18)$$

$$Cpk = \min\left\{ \frac{USL - \overline{X}}{3\sigma}, \frac{\overline{X} - LSL}{3\sigma} \right\}$$

Process Control is King!



Western Electric (WECO) Rules for Detecting Out Of Control or Non-Random Systems

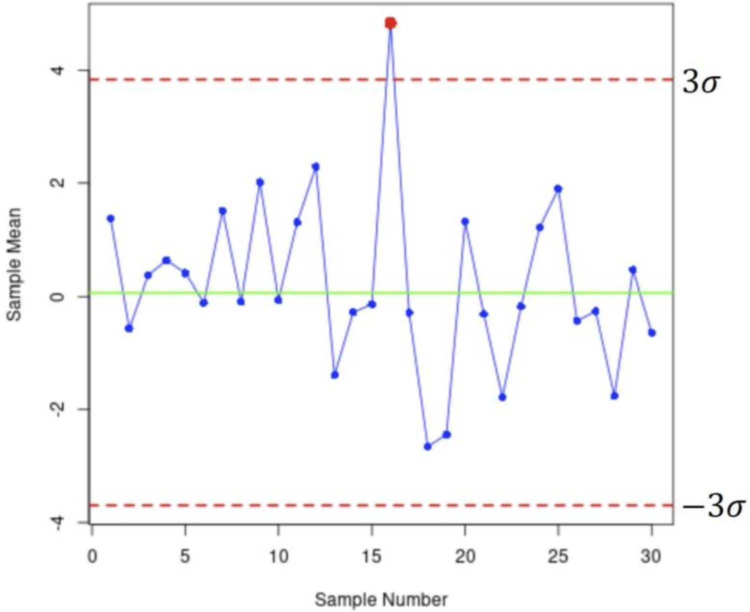
Any one of the following conditions offers evidence that a process is not in control:

- Any point above the upper 3σ or below the lower 3σ control limits
- Two out of the last three points above the upper 2σ or below the lower 2σ control limits
- Four out of the last five points above the upper 1σ or below the lower 1σ control limits
- Eight consecutive points on the same side (above or below) the center line.

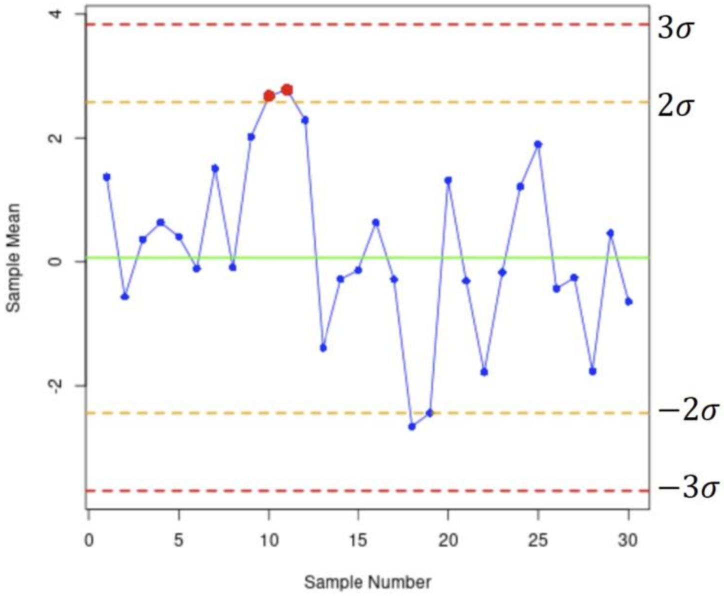
Additional Nelson Rules were developed in the 1950s.

- Six points in a row ascending or descending.
- Fifteen points in a row “hugging” the center line between $+1\sigma$ and -1σ.
- Fourteen points in a row alternating up and down.

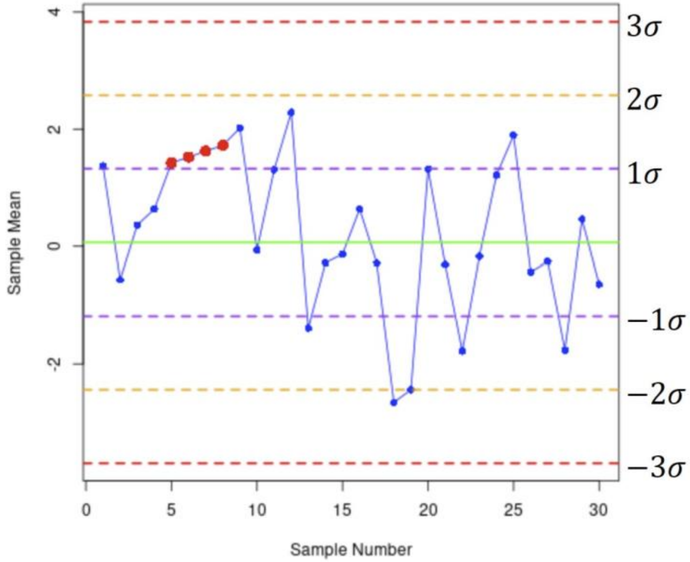
Process Control is King!



Process Control is King!



Process Control is King!



Process Control is King!

- A powerful formula… Poisson’s yield model

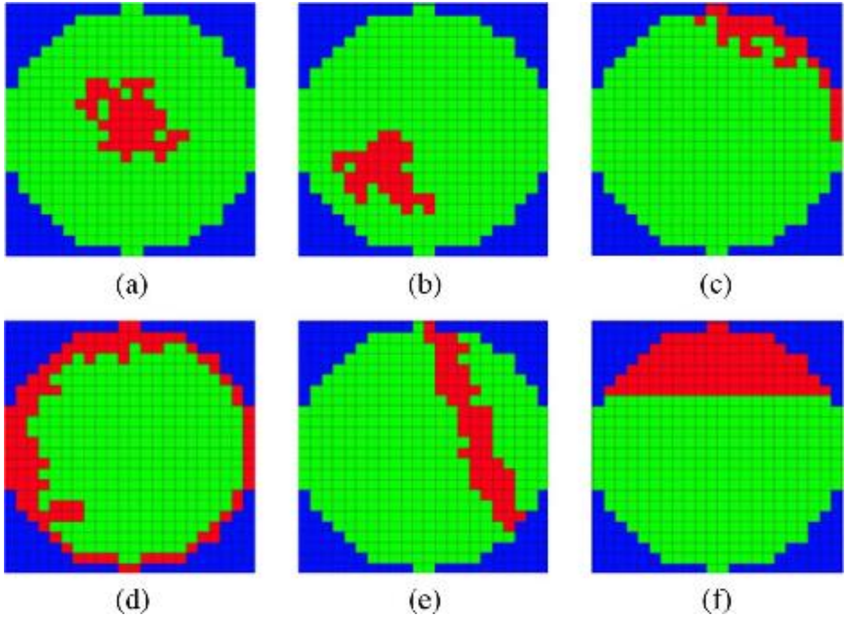
- A_c Die area (cm^2)
- D_0 Defect density (Defect/cm^2)

$$Y = \exp\left(-A_C D_O\right)$$

Lets play with this a bit…

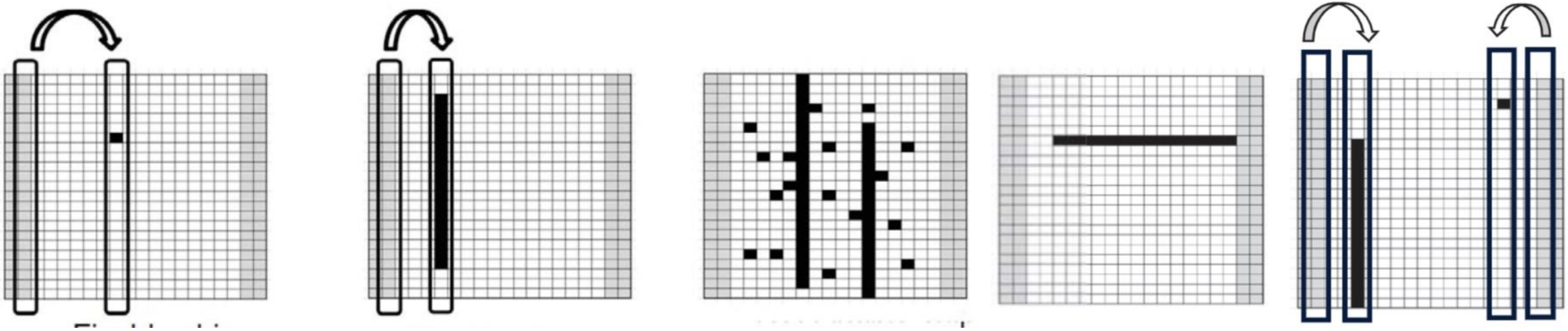
https://www.desmos.com/calculator/1a1nhlpjzv

Process Control is King!



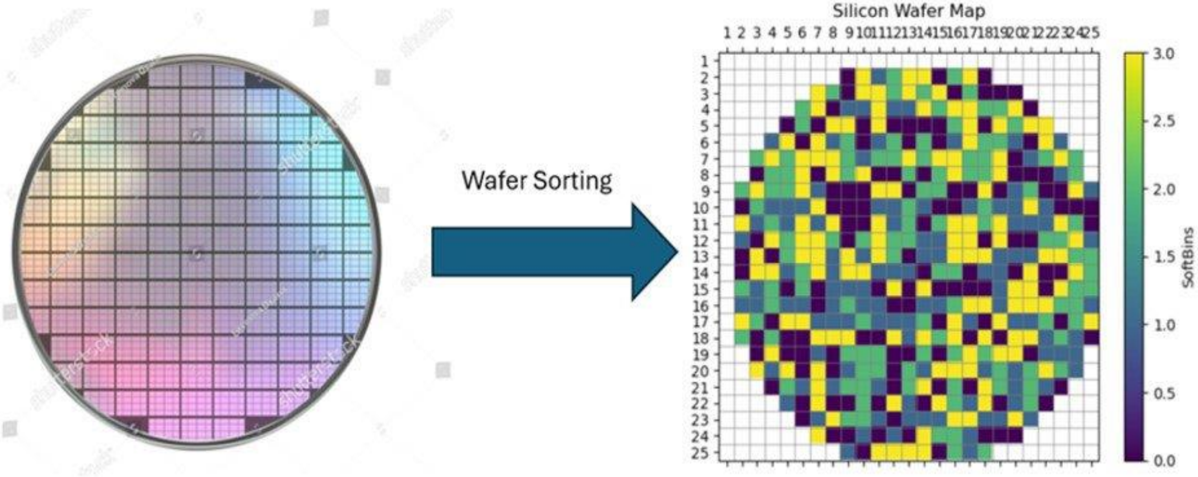
Beating the system: Redundancy

Beating the System as a Designer (Memory)



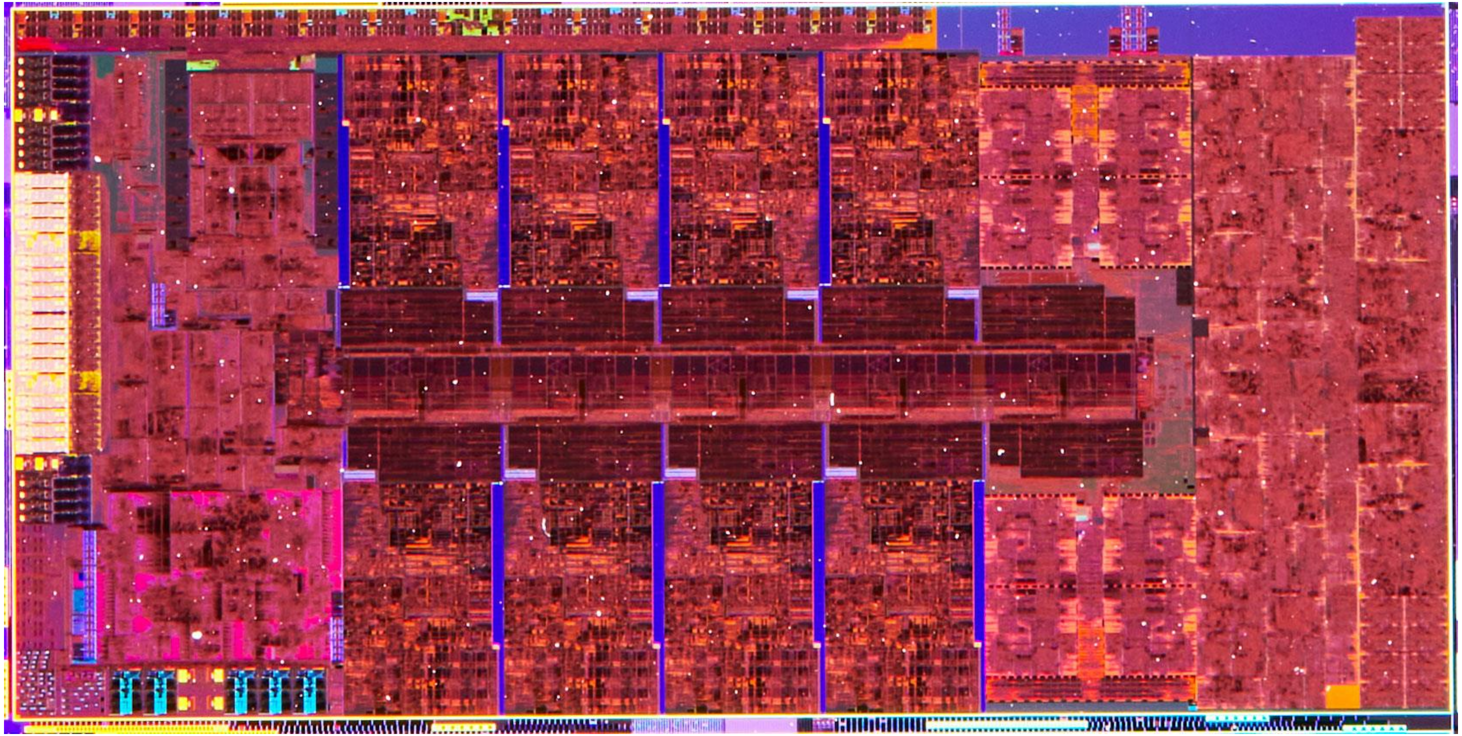
One Man’s trash… (Binning)

One Man’s Trash…



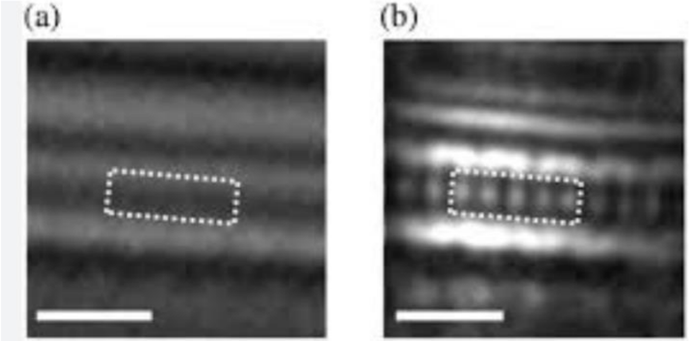
An untested wafer goes through sorting (testing) process. A computer-generated map as a result (right).

One Man’s Trash… (12900K -> 12500K)



Measure Twice, Cut Once (Optical Microscopy)

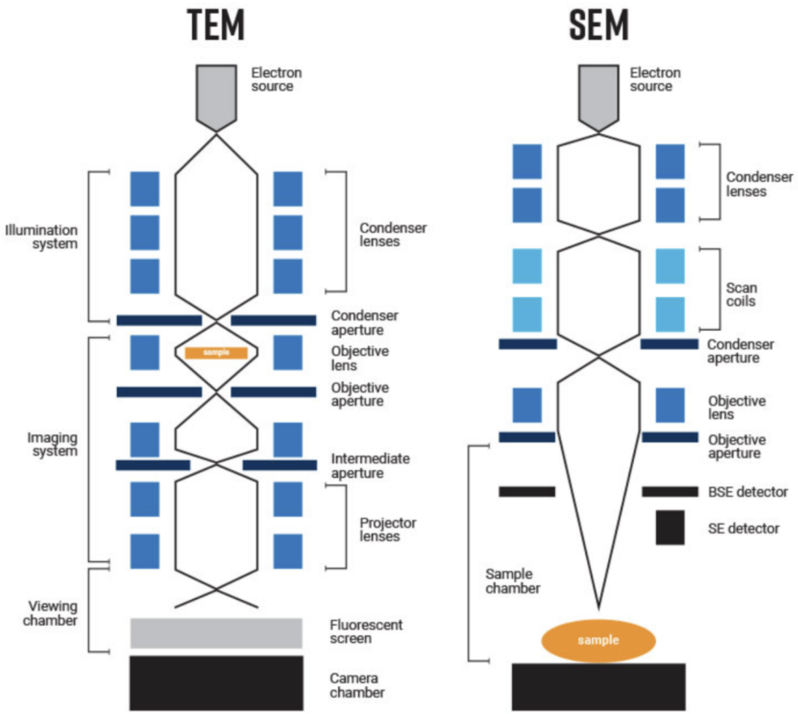
- Fast, Cheap and Efficient
- Imperfect identification of defects
- In-line inspection, can use pattern recognition when scanning over multiple dies
- Bright/dull spots will say “something is probably wrong”
- Better in packaging/large metallization layers
- ~200nm resolution



https://opg.optica.org/ol/fulltext.cfm?uri=ol-45-22-6218&id=442518

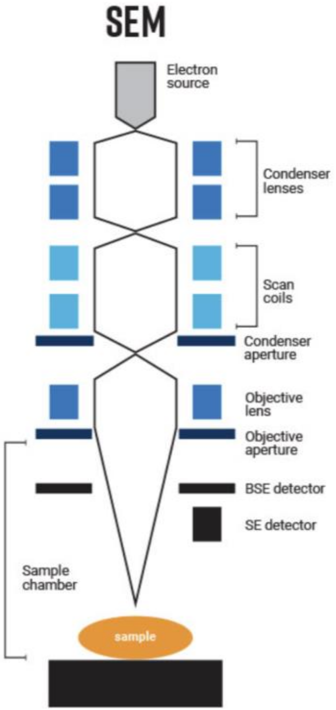
Measure Twice, Cut Once (Electron Beam Microscopy)

- Expensive, hard to put in-line
- Can damage/destroy sample
- Extremely good resolution
- Can potentially see individual atoms
- Too slow for most high volume, in-line applications

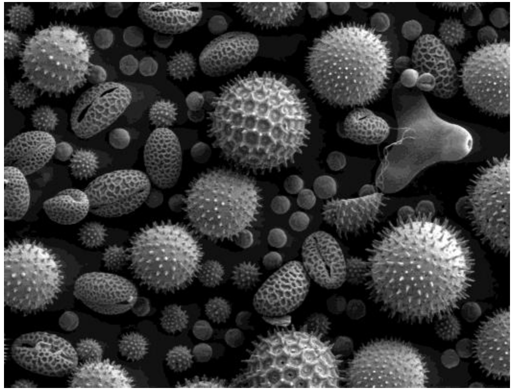


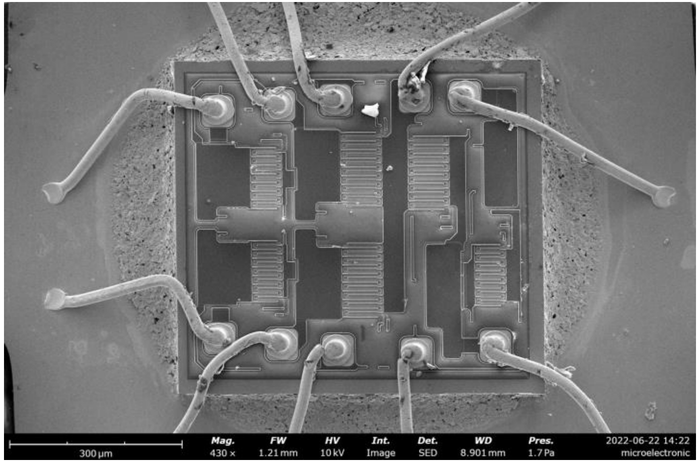
Measure Twice, Cut Once (Scanning Electron-Beam Microscopy)

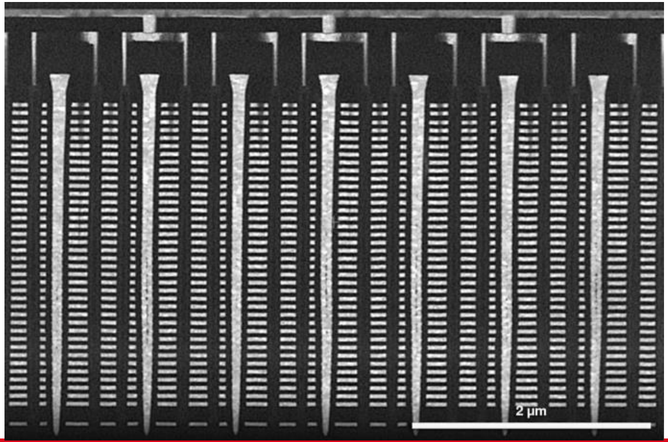
- Medusa?
- ~1-10 nm resolution
- Higher power = Higher Resolution
- <1kV used by fabs, can use >30kV (Why?)



Measure Twice, Cut Once (Electron Beam Microscopy)

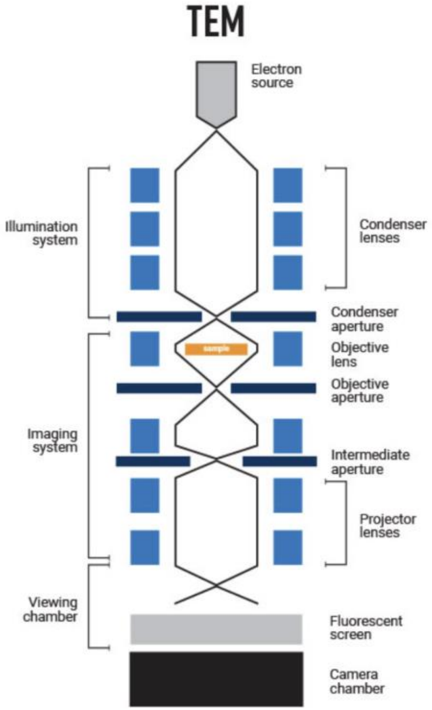




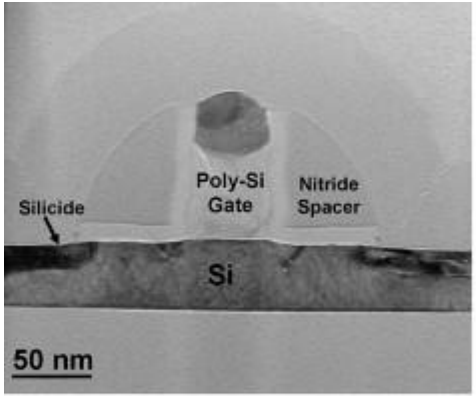


Measure Twice, Cut Once (Transmission Electron-Beam Microscopy)

- Semiconductor as glass
- Extremely thin samples
- Sample WILL be destroyed in process (<200nm max thickness)
- Impractical for large sampling requirements
- ~0.1-0.5nm resolution



Measure Twice, Cut Once (Electron Beam Microscopy)



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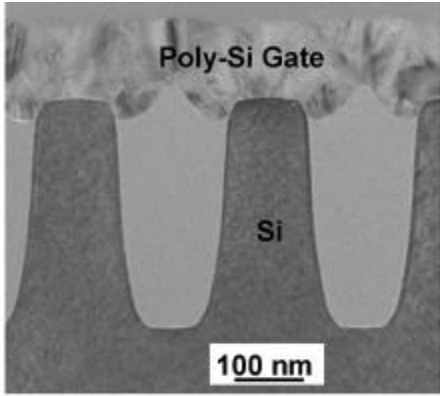

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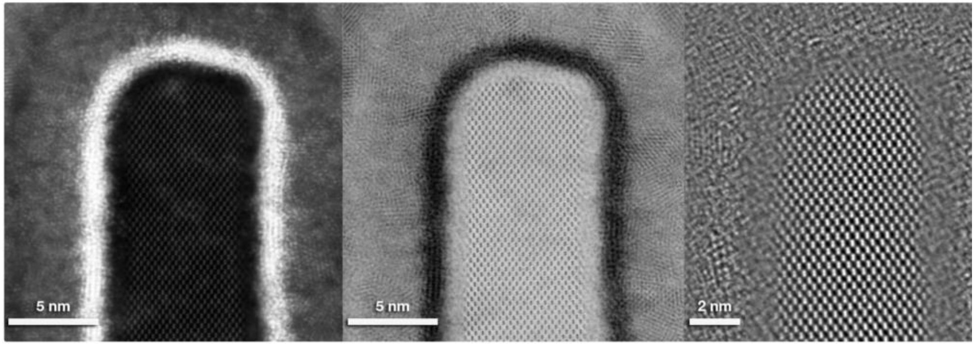
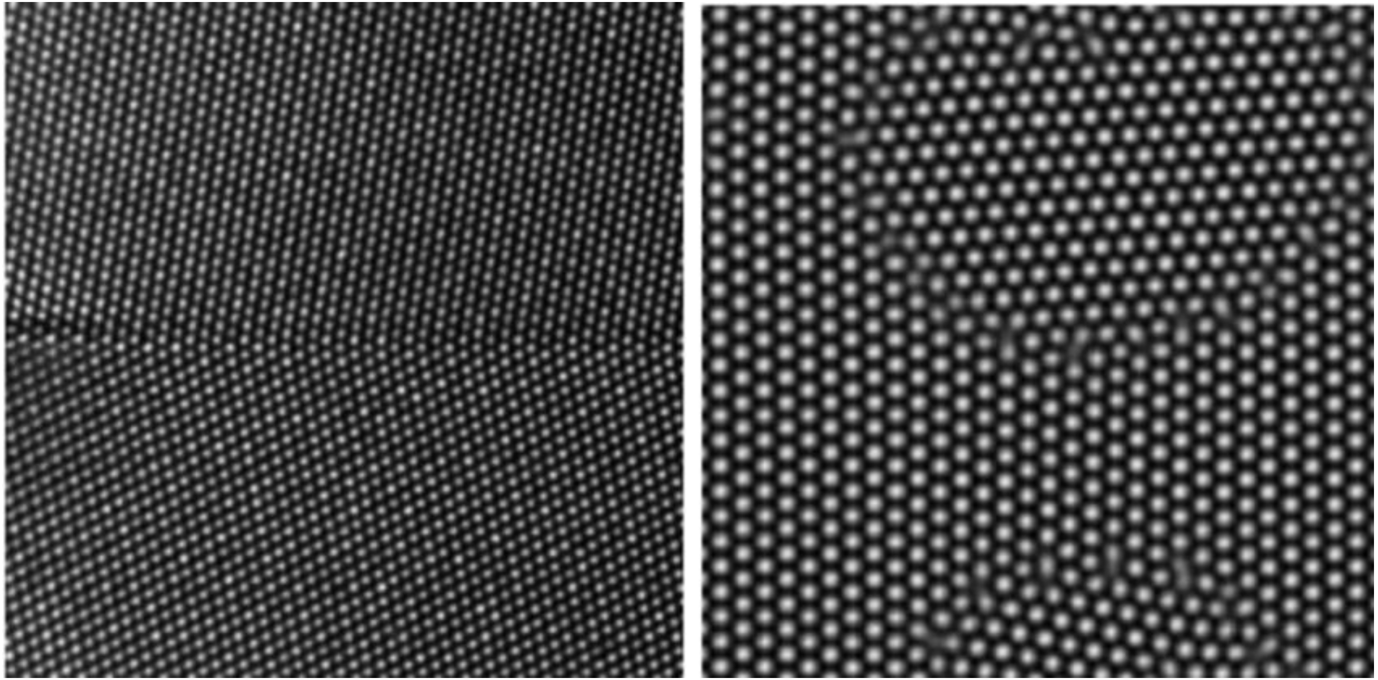
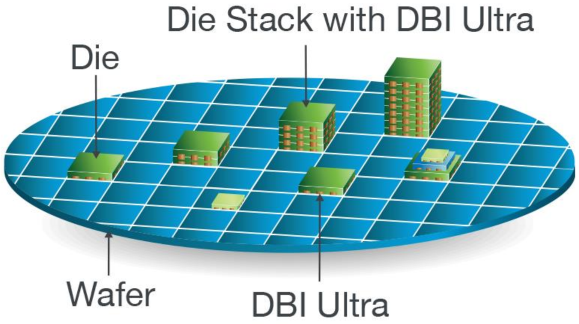
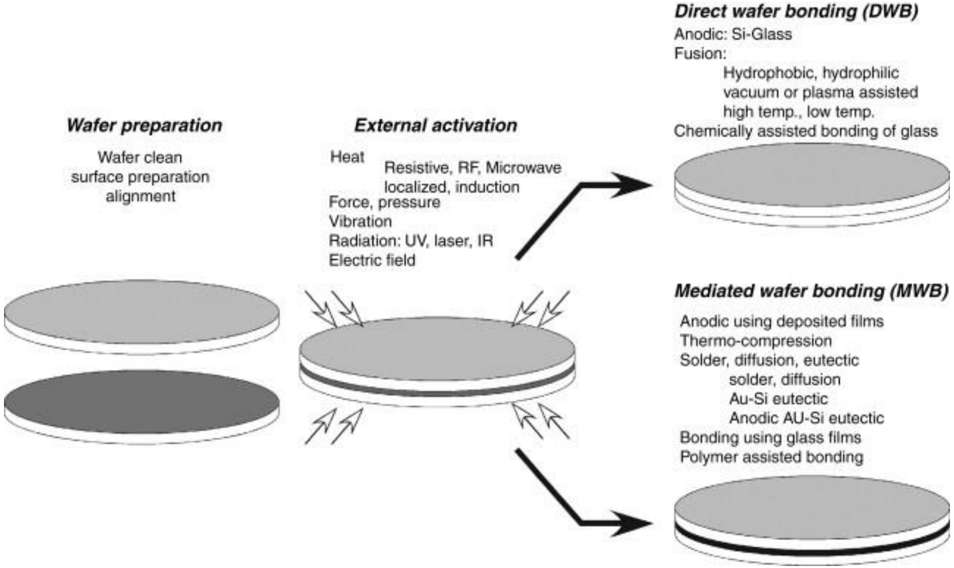


Measure Twice, Cut Once (Electron Beam Microscopy)



Overview (HI)


Die Stack with DBI Ultra
Die
Wafer
DBI Ultra


Wafer preparation
Wafer clean
surface preparation
alignment
External activation
Heat
Resistive, RF, Microwave
localized, induction
Force, pressure
Vibration
Radiation: UV, laser, IR
Electric field
Direct wafer bonding (DWB)
Anodic: Si-Glass
Fusion:
Hydrophobic, hydrophilic
vacuum or plasma assisted
high temp., low temp.
Chemically assisted bonding of glass
Mediated wafer bonding (MWB)
Anodic using deposited films
Thermo-compression
Solder, diffusion, eutectic
solder, diffusion
Au-Si eutectic
Anodic AU-Si eutectic
Bonding using glass films
Polymer assisted bonding

Overview

- Fabs cost billions to run. Increasing yield by a few %=millions to billions in profit
- Improvement in understanding of tech
- Upfront cost is typically worth it
- Yield Engineering
- Test Engineering
- Failure Analysis Engineering

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