ECE 510 Lecture 16
Manufacturing Test Methods, ct'd

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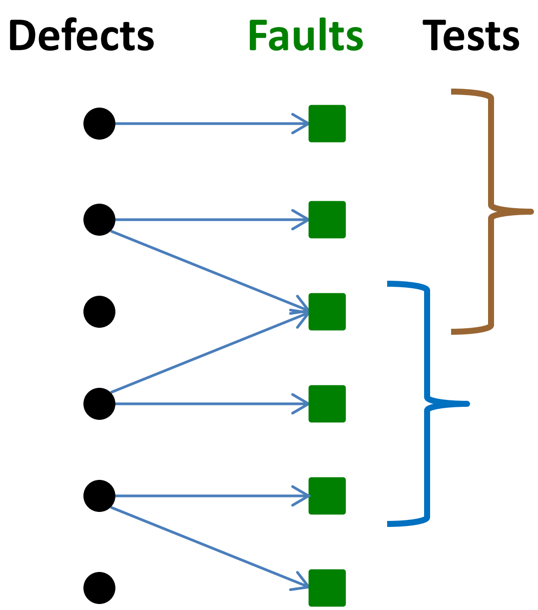
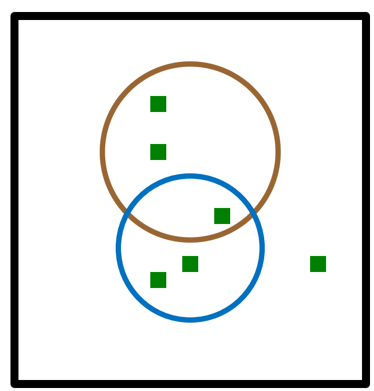
Outline

- Manufacturing Test Flow
- Purpose of Various “Test Modules”.
- Monitors: Containing Risk in High-Volume Manufacturing
- What’s Inside a “Test Module”.
- Mutual Coverage of Tests and Patterns.
- Stop-on-Fail (SOF) Figures of Merit from Coverage Metrics
- Measuring Mutual Coverage with Continue-on-Fail (COF) Data

Defects vs Faults

- Tests detect faults. A fault is a circuit malfunction.
- A given test detects only a fraction ("coverage") of all possible faults.
- Different tests detecting the same fault have mutual coverage.
- Faults are caused by defects. Tests don't directly detect defects.
- A given defect may cause no faults, one fault, or multiple faults.
- Probability of "fault activation" depends on probability of defects.
- Probability of test failure depends on probability of "fault activation", and test fault coverage.



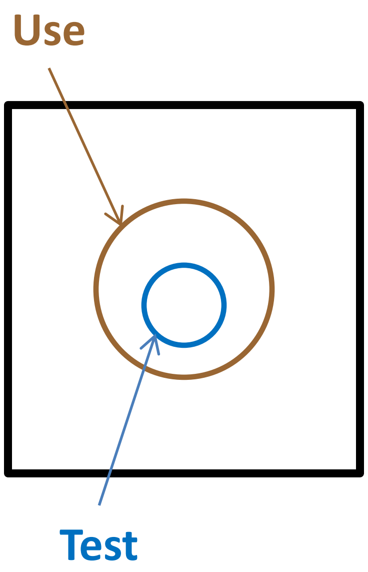


A chip only fails when

1. A fault is "activated" by a physical defect.
2. A test is present which can detect the fault.

Williams Brown Model

- Derived here in a different way from the original.
  - Uses the Poisson approximation.
- Suppose
  - λ_{Test} is the average number of activated faults in the chip detected by Test.
  - λ_{Use} is the average number of activated faults in the chip detected by Use.
- Then the fraction of chips good in Use and in Test is



$$Y_{Use} = \exp(-\lambda_{Use}), \quad Y_{Test} = \exp(-\lambda_{Test})$$

- And the user-perceived fraction defective is

$$DL = \frac{Y_{Test} - Y_{Use}}{Y_{Test}} = 1 - \exp\left[-(\lambda_{Use} - \lambda_{Test})\right] = 1 - \left[\exp(-\lambda_{Use})\right]^{1-\frac{\lambda_{Test}}{\lambda_{Use}}} = 1 - Y_{Use}{}^{1-c}$$

- Coverage, *c*, and transparency, *t*, are defined as

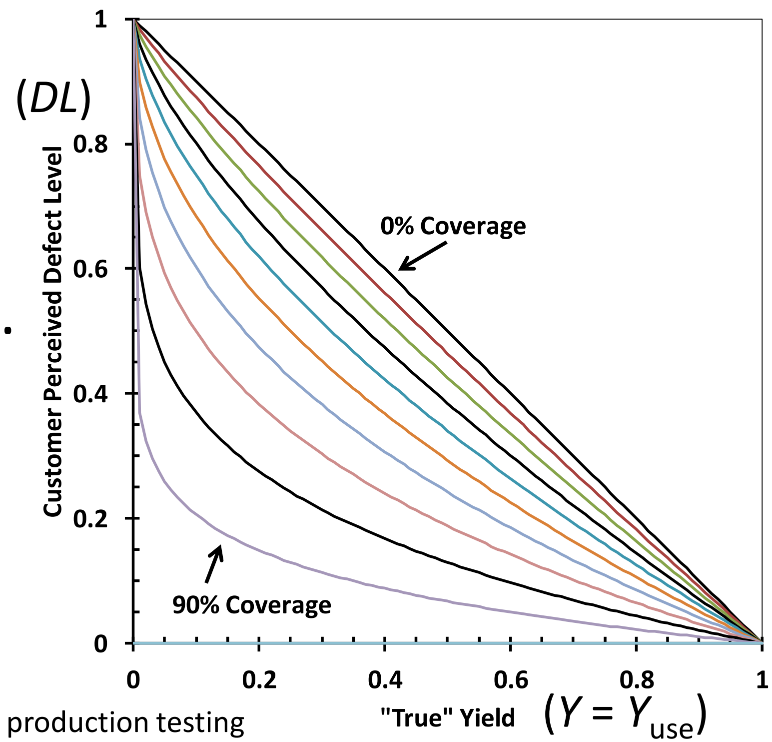
$$c \equiv 1 - t \equiv \frac{\lambda_{Test}}{\lambda_{Use}}$$

T. **W. Williams and N. C. Brown**, Defect Level as a Function of Fault Coverage," IEEE Transactions on Computers, Vol. C-30, No. 12 (1981), pp987-988. http://dx.doi.org/10.1109/TC.1981.1675742

Williams Brown Model, ct'd

- Y
  - Is the fraction of dies "good" in Use without any testing (c = 0).
  - Measures defectivity of the Fab process.
  - Is "owned" by the Fab process.
- c
  - Measures the quality of the Test.
  - Is "owned" by product design.
- WB shows the tradeoff between Fab defectivity and Test coverage.
- There are other models...

$$DL = 1 - Y^{1-c}$$



$$DL = \frac{(1-c)(1-Y)\exp[-(n_0-1)c]}{Y+(1-c)(1-Y)\exp[-(n_0-1)c]}$$

Provides an adjustable parameter, n_0.

Agrawal, V.D.; Seth, S.C.; Agrawal, P.; , "Fault coverage requirement in production testing of LSI circuits," IEEE Journal of Solid-State Circuits, vol.17, no.1, pp. 57- 61, Feb 1982 http://dx.doi.org/10.1109/JSSC.1982.1051686

Example

- For a fab yield of 90%, what test coverage is required to satisfy a customer-perceived quality level of 1000 DPPM or better?

$$DL = 1 - Y^{1-c}$$

$$Y^{1-c} = 1 - DL$$

$$(1-c)\ln Y = \ln(1-DL)$$

$$1-c = \frac{\ln(1-DL)}{\ln Y}$$

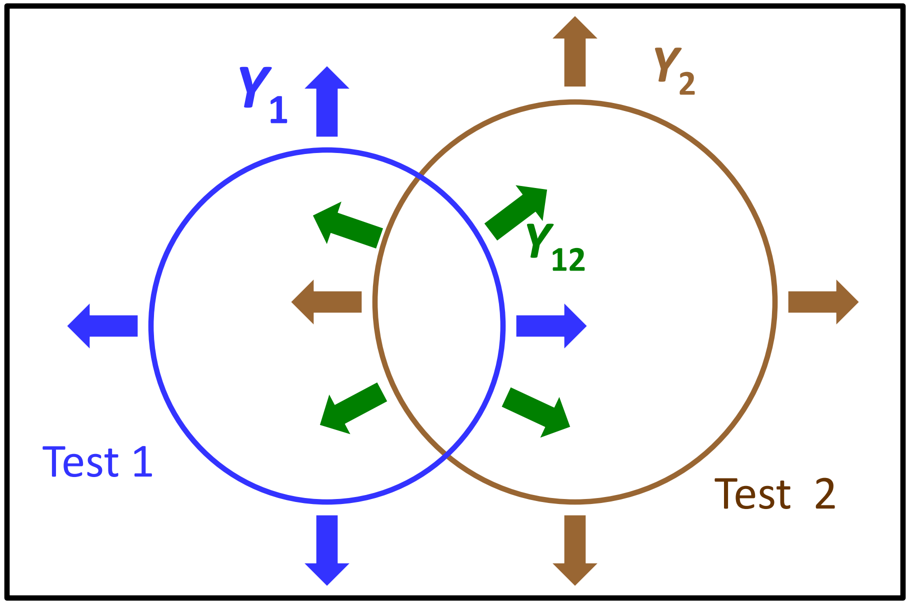
$$c = 1 - \frac{\ln(1-DL)}{\ln Y} = 1 - \frac{\ln(1-1000\times 10^{-6})}{\ln(0.9)} = 1 - \frac{\ln(1-.001)}{\ln(0.9)}$$

$$= 1 - \frac{\ln(0.999)}{\ln(0.9)} = 1 - \frac{(-0.0010)}{(-0.1054)} = 1 - 0.0095 = 99.05\%$$

- Required test coverage is 99.05% or more.

Joint Yields

- Joint yields can be measured from continue-on-fail (COF) data.



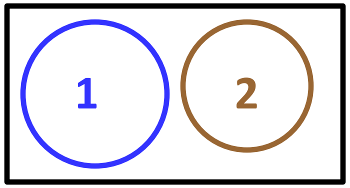
- Circles are faults covered by Tests.
- So area outside circles represents the yield of the Test.

Y_1 = Fraction of Population Good in Test 1, “don’t care” in any other Test.
Y_2 = Fraction of Population Good in Test 2, “don’t care” in any other Test.
Y_{12} = Fraction of Population Good in Test 1 and in Test 2, “don’t care” in any other Test

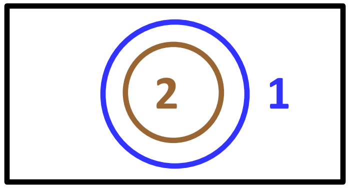
- Obvious generalization to more than 2 Tests.

Rules for Joint Yields

- Independent Tests.
  - Tests which never cover a common fault, such as tests which cover completely different parts of the circuit.
  - Assumes that faults which are not common are also uncorrelated. That is, the ocurrence of one does not affect the other.
  - $Y_{12} = Y_1 \times Y_2$



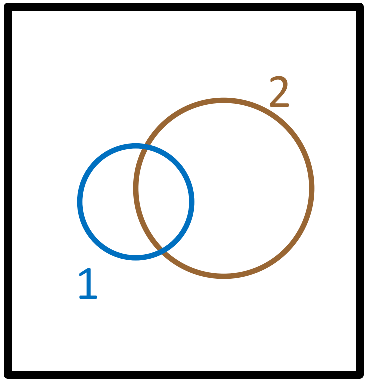
- One Test fully covers another.
  - Test 1 covers all faults in Test2 (but not vice versa)
  - $Y_{12} = Y_1$
  - Special case for pattern coverage. Tests cover the same faults, except by a factor which increases the number of faults covered without uncovering any.
  - $Y_{12} = \min[Y_1, Y_2]$



Coverage Metric

- General

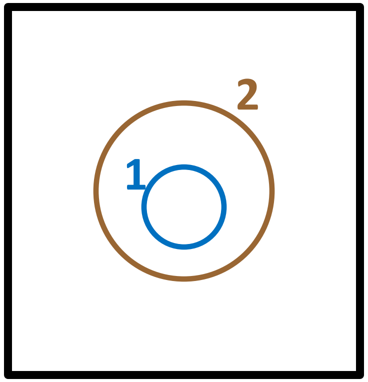
$$\text{Coverage of Test 2 by Test 1} = 1 + \frac{\ln Y_1 - \ln Y_{12}}{\ln Y_2}$$



- Special case 1: Test 2 completely covers Test 1.
  - In this case, $Y_{12} = Y_2$

$$\text{Coverage of Test 2 by Test 1} = c_{2|1} = 1 + \frac{\ln Y_1 - \ln Y_{12}}{\ln Y_2} = \frac{\ln Y_1}{\ln Y_2}$$

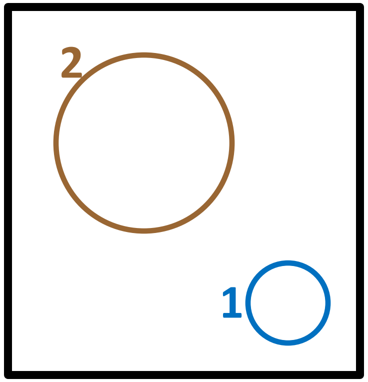
$$\text{Coverage of Test 1 by Test 2} = c_{1|2} = 1 + \frac{\ln Y_2 - \ln Y_{12}}{\ln Y_1} = 1$$



  - WB recovered when $DL = (Y_1 - Y_2)/Y_1$
- Special case: Independent Tests.
  - In this case $Y_{12} = Y_1 \times Y_2$ and mutual coverage vanishes.

$$\text{Coverage of Test 2 by Test 1} = c_{2|1} = 1 + \frac{\ln Y_1 - \ln Y_1 - \ln Y_2}{\ln Y_2} = 0$$

$$\text{Coverage of Test 1 by Test 2} = c_{1|2} = 1 + \frac{\ln Y_2 - \ln Y_1 - \ln Y_2}{\ln Y_1} = 0$$



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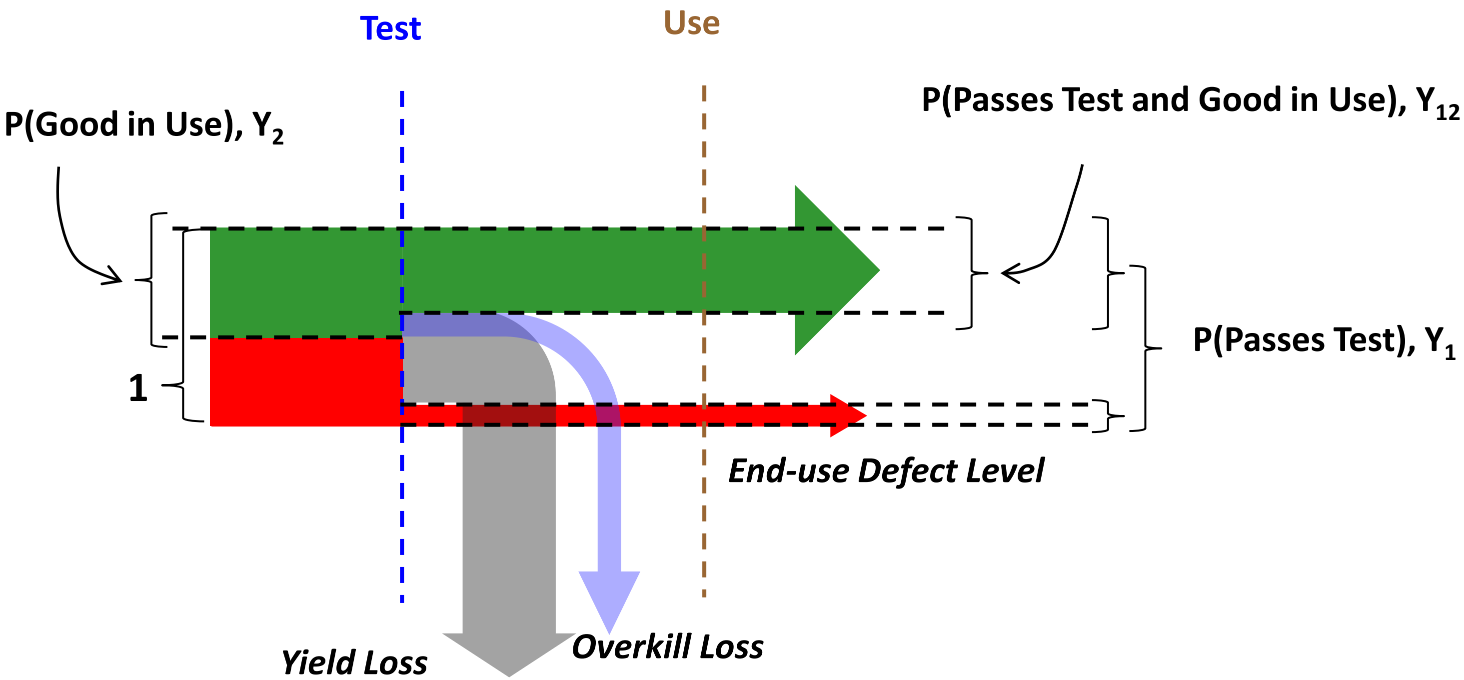
FOMs from Joint Yields

- Assume that Test 1 is a screen (Stop-on-Fail, SOF), and Test 2 is Use..
- There are 3 figures of merit for Test 1

$YL = 1 - Y_1$ (Yield Loss)

$OL = Y_2 - Y_{12}$ (Overkill)

$DL = 1 - \frac{Y_{12}}{Y_1}$ (Fraction failing at Test 2)



Test Time From Joint Yields

- Suppose that test *n* has average TTG g_n, and average TTB, b_n.
  - Usually $g_n > b_n$.
- What is the average test time for a stop-on-fail (SOF) test process?

$$
\begin{aligned}
TT &= Y_1 g_1 + (1-Y_1) b_1 \\
&\quad + Y_1 \left(Y_{2|1} g_2 + (1-Y_{2|1}) b_2 \right) \\
&\quad + Y_{12} \left(Y_{3|12} g_3 + (1-Y_{3|12}) b_3 \right) \\
&\quad + ..
\end{aligned}
$$

$$
\begin{aligned}
&= Y_1 g_1 + (1-Y_1) b_1 \\
&\quad + Y_{12} g_2 + (Y_1 - Y_{12}) b_2 \\
&\quad + Y_{123} g_3 + (Y_{12} - Y_{123}) b_3 \\
&\quad + ..
\end{aligned}
$$

- What-if may be done by shuffling 1,2,3,.. labels among tests.
  - Generally push short TT (small g_n) and/or low-yield tests to the beginning.
  - High coverage of a test makes all downstream TTB contributions vanish.
    - eg. if 1 covers all, then $Y_1 = Y_{12} = Y_{13} = Y_{123} = ..$

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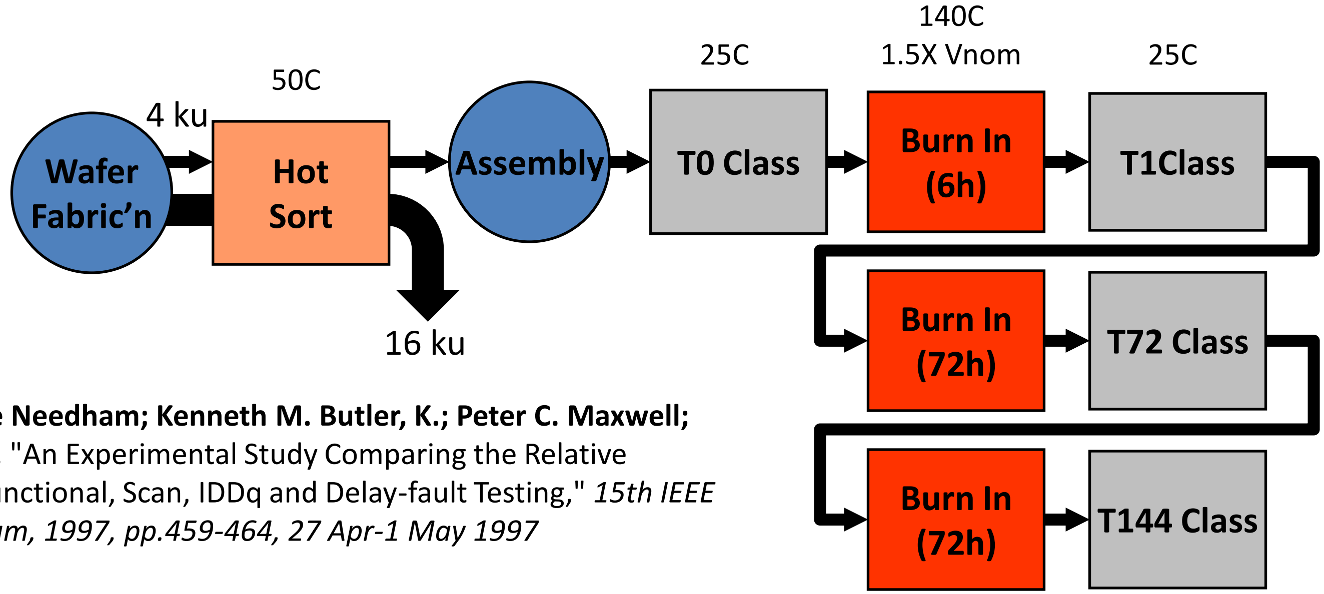
  - Sematech Data, Software Tools

Sematech Experiment

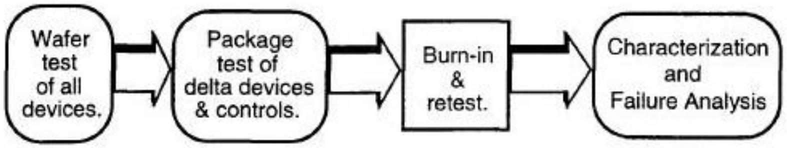
- A 1997 experiment to produce a dataset for research and teaching.
  - Published in the open literature. Data publicly available.
- Comparative study of
  - Functional, Scan, Iddq, and Delay test methods.
- Continue-on-Fail experiment.
  - Failing units continue in the test flow so that full data can be accumulated.
  - 20000 units were tested at Sort.
  - 4000 units were packaged and went through burn in.



Phil Nigh, ; Wayne Needham; Kenneth M. Butler, K.; Peter C. Maxwell; Robert C. Aitken; , "An Experimental Study Comparing the Relative Effectiveness of Functional, Scan, IDDq and Delay-fault Testing," *15th IEEE VLSI Test Symposium, 1997, pp.459-464, 27 Apr-1 May 1997*

Sematech Experiment

- Major project Steps



- Experimental Flow

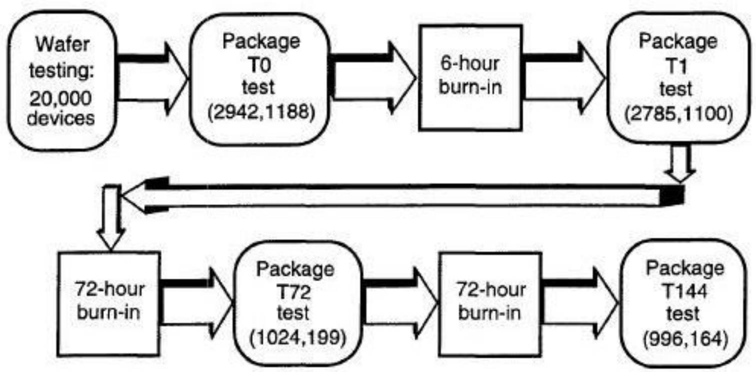


Figure 4. Experiment flow. The numbers in parenthesis represent the number of delta devices and control devices at each test step.

- Both good and failing devices are sent into subsequent tests.
  - Control devices: Good in all tests at Sort.
  - Delta devices: Failing in some, but not all, tests at Sort.

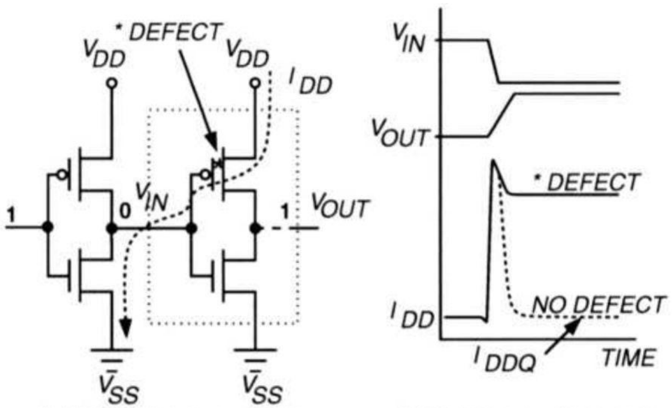
Description of Tests

- Power-Up Tests
  - Gross power supply short.
  - Signal Input/Output
- Stuck-At Fault Test.
  - 8023 scan vectors generated from stuck-at fault model.
- Functional Tests
  - 532k vectors not involving scan, related to function of the chip.
- Delay Tests
  - 5232 vectors utilizing the scan chain to launch/capture patterns.
- Iddq Tests
  - 195 vectors. Each puts the chip into a quiescent state and then overall device leakage is measured.
- Scan Flush
  - A single test measuring the transit time along scan chain(s).

For Stuck-At and Delay..

How does scan work?

For Iddq..



(a) CMOS inverter circuit. (b) Voltages and currents.

Description of Chip

- IBM ASIC. Bus Interface Controller.
- 0.45 um technology node (1997), 50 MHz, Vdd = 3.3V
- Die size 9.4 x 8.8 mm^2
- Package: 304 pin C4 flat pack
- 249 signal pads, 20 power pads.
- DFT
  - boundary scan
  - 8 scan chains
  - Iddq testable (design has zero static current)

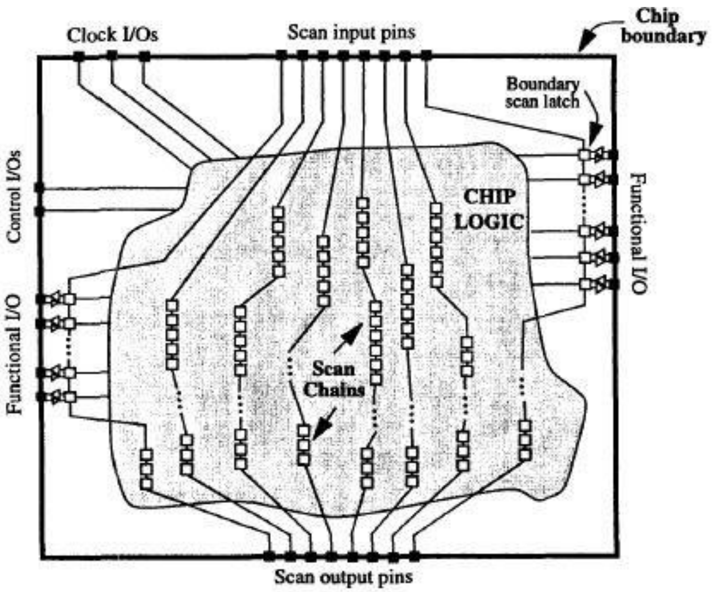


Figure 2. Chip architecture showing scan design architecture and boundary scan. (The scan input and output pins are also used as functional I/O. This is controlled by mux circuitry that is not shown.)

Description of Data

- Open Excel document.
  - sematech_chipdata_cleaned_up.xlsb or .csv
- Concepts:
  - Fields, Records, Role of nulls.
  - Continue-on-fail (COF) vs Stop-on-fail (SOF)
  - Attribute vs Variable.
  - csv (comma-delimited) files.
- Differences between Sematech data and real data.
  - Sematech is small. Only 18466 records, 233 fields.
  - Real data may have > 1 million records.
  - Real data has time stamps.
  - Sematech data has been heavily processed to summarize results into categories, eliminate almost duplicate records, etc.
    - Real data is much messier!
  - Sematech data is COF.

Tools

- Excel and SQLite/GUI are complementary tools.
  - Linked by import/export functionality.
  - Comma-delimited (.csv) files are the “lingua-franca”.
- Excel
  - Great for quickly viewing and filtering of data.
  - Good for column-to-column calculations. Plenty of statistical functions, custom functions are easy to add.
  - Useful user-written tools are available, but JMP and others may be better.
    - Single Plotter – Make CDF, PDF plots of a single field.
    - Multi Plotter – Make correlation plots of up to 6 fields. RankAvg is available to make rank correlation plots.
    - Wafer Mapper. Make wafer maps of any field for XY-grouped data.
  - Not good for restructuring data, aggregating, counting, etc.. Pivot tables can do aggregating, but are awkward and limited.

Tools, ct'd

- SQL Database Software
  - Only a subset of functionality is needed. For example..
  - SQLite is a simple one-user program. The single user CLI is free and is installed by default on PCs, Linux, etc.
  - SQLite Expert Professional is a GUI for SQLite. ($59 x 0.65 = $38, or free for a month). Personal edition is free but unacceptably crippled (export disabled).
- Structured Query Language (SQL)
  - Our focus is on querying a database in a single-user context. Not on designing a database, or on a multi-user environment.
  - SQL is essential for reorganizing, counting, finding/testing uniqueness, aggregating, joining tables, reorganizing data, Boolean operations on data, defining categories.
  - Processes data row-by-row. Not good at col-to-col math.

Clare Churcher, Beginning SQL Queries: From Novice to Professional, 1st edition Apress (2008)

Examples

- Data integrity checks based on counts. eg. Number of records per Lot/Wafer/xy should be 1.
- Paretos (Example 9)
- Pattern coverage.
  - Use Single Plotter (Fine Bins) Rev 5.xlsb to plot pattern dist'ns.
- Wafer Maps (Examples 8, 11, 13)
  - Use WaferMapper Rev 1.xlsb
- Measuring Coverage
  - Use sematech_chipdata_cleaned_up.xlsb

Example: Measuring Coverage

- Delay Test at 3 different VDD's: Nom, Hi, Low.
- What is the coverage of Nom, Hi or Low alone compared to a screen with all 3 tests? Which is the best single test to replace doing all 3?

$$\text{Total Units} = 13419 + 326 + 7 + 4487 + 39 + 10 + 7 + 36 = 18331$$

$$Y_{All} = \frac{13419}{18331} = 0.732039$$

$$Y_{Nom} = \frac{13419 + 326 + 7 + 10}{18331} = 0.750750$$

$$Y_{Hi} = \frac{13419 + 10 + 7 + 36}{18331} = 0.734930$$

$$Y_{Lo} = \frac{13419 + 326 + 39 + 36}{18331} = 0.753914$$

$$c_{Nom} = \frac{\ln(Y_{Nom})}{\ln(Y_{All})} = 0.919$$

$$c_{Hi} = \frac{\ln(Y_{Hi})}{\ln(Y_{All})} = 0.987$$

$$c_{Lo} = \frac{\ln(Y_{Lo})}{\ln(Y_{All})} = 0.906$$

If you have to pick a single test to replace all 3, Hi has the best coverage.