

Semiconductor Manufacturing and Engineering Data Analysis

Michael Hackerott

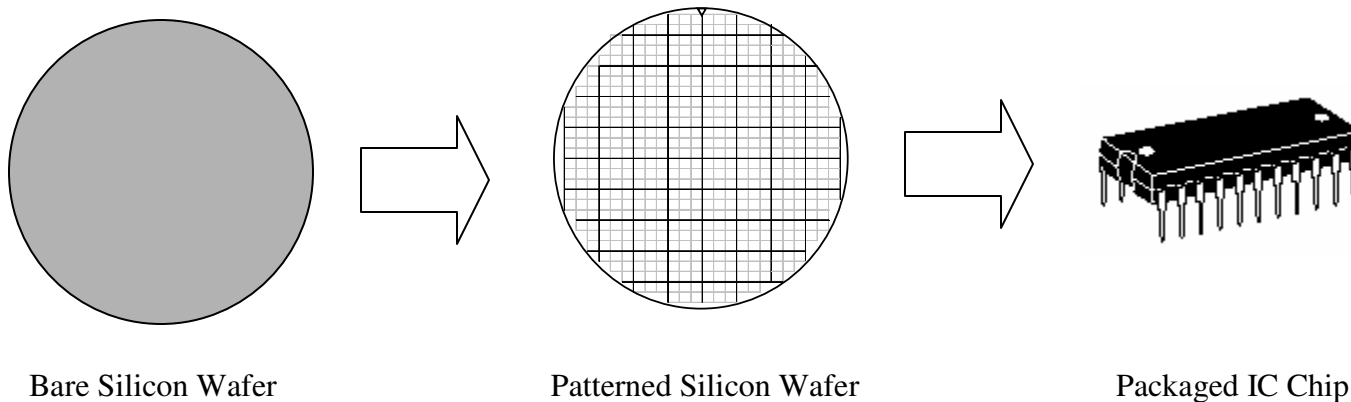
Email: michael.hackerott@cox-internet.com

Forward

- This presentation is intended to provide an overview of Semiconductor Manufacturing and Engineering Data Analysis, and their relationship
- The presentation consists of an explanation of:
 - generic Semiconductor Manufacturing process steps
 - a generic Engineering Data Analysis system
 - each of the different engineering disciplines involved in Semiconductor Manufacturing and Engineering Data Analysis
 - the characteristics of each of the simple types of semiconductor devices
 - the effect of operating temperature on semiconductor devices
 - an analysis of complex IC operating frequency and current

Semiconductor Manufacturing and Engineering Data Analysis

- Semiconductor manufacturing is the process of taking bare silicon “wafers” and repetitively processing them by adding layers of material that are then patterned into “integrated circuits” which are cut into individual “chips” that are packaged for use in an electronic system
- Semiconductor Manufacturing is a complex process consisting of hundreds of manufacturing steps
- In order to monitor and control the manufacturing process, data is collected at many of the manufacturing steps
- Engineering Data Analysis is the statistical analysis of data collected during the semiconductor manufacturing process



Yield!

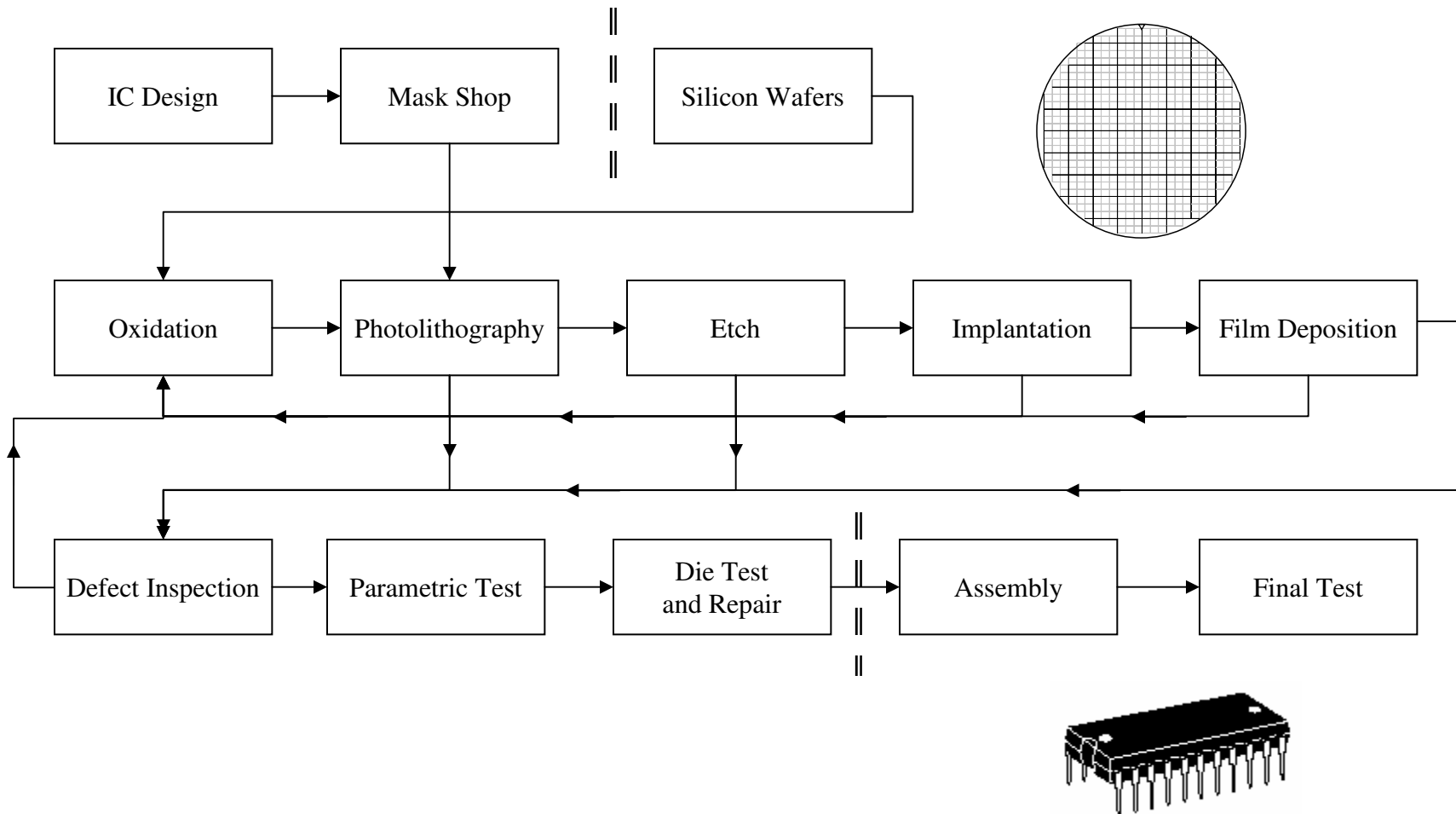
- The ideal goal of the semiconductor manufacturing processes is to make each individual integrated circuit perform to specification
- However, physical defects induced during processing and variation in processing causes some individual integrated circuits to fail to perform to specification
- The ratio of individual integrated circuits that perform to specification, “good”, to the total number of circuits is called “yield”:

$$\text{Yield} = \frac{\text{Good}}{\text{Total}} \%$$

- The yield is typically expressed as a percentage
- In addition to monitoring and controlling processing, Engineering Data Analysis is key to identifying why integrated circuits do not perform to specification
- A yield can be defined for each semiconductor manufacturing step. The overall yield is then the product of the step yields

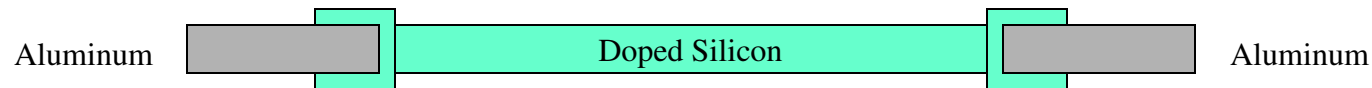
$$Y_T = Y_1 * Y_2 * \dots * Y_N$$

Semiconductor Manufacturing Process Steps



Integrated Circuit Design

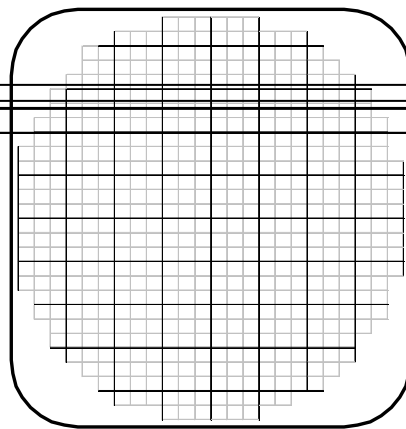
- Integrated Circuit Design is the process of implementing electrical circuit functionality using semiconductor materials
- For example, a simple resistor, a device that opposes the flow of current, can be created by sizing and doping an area of silicon appropriately. Additionally, a method to connect the resistive silicon to external wires must be included



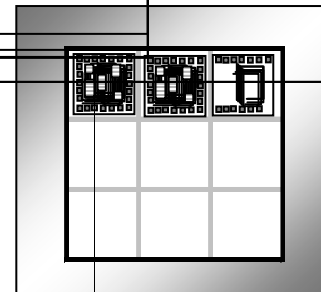
- Other, simple devices such as transistors, diodes, and capacitors can be formed from semiconducting materials
- A complete Integrated Circuit can contain millions of these simple devices working together to perform complex functions as a Microprocessor, Digital Signal Processor, Memory, etc
- The Designer must implement the final complex functionality from simple devices
- Integrated Circuit Design is done using computers with advanced circuit design and layout software tools
- The final Integrated Circuit Design is a “database” of the electrical and physical characteristics of the complex device
- Multiple layers of geometric shapes of semiconductor materials are defined that can then be implemented by “wafer fabrication”

Mask Shop

- An Integrated Circuit design is translated into a series of “layers” that are vertically integrated to produce electrical circuits
- The Mask Shop takes a design database as input and outputs “masks” or “reticles” for each layer that will be required for wafer fabrication
 - Masks and reticles are pieces of very clear glass covered with an opaque material in the geometric patterns appropriate for each layer
 - A “mask” is a large device that has the patterns for each unique integrated circuit on the wafer on it
 - A “reticle” is a small device that has the patterns for a few unique integrated circuit for a small area of a wafer on it
- Typical designs have 20 to 40 layers that form the complete integrated circuit



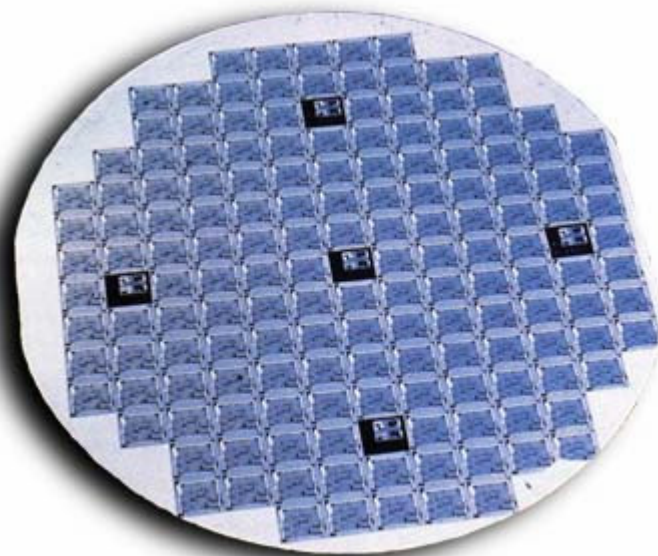
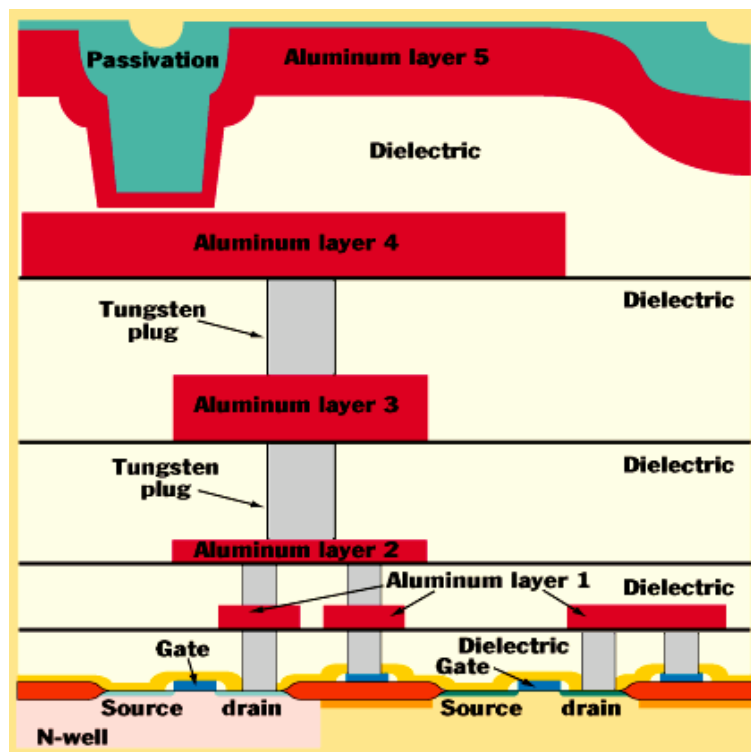
Mask
(10's to 100's of IC)



Reticle
(several IC)

Wafer Fabrication

- The series of the semiconductor manufacturing steps performed on wafers is referred to as “wafer fabrication”
- After 20 to 30 layers of wafer processing are performed the result is a wafer containing many complete integrated circuits
- The area of a single complete integrated circuit is called a “die”



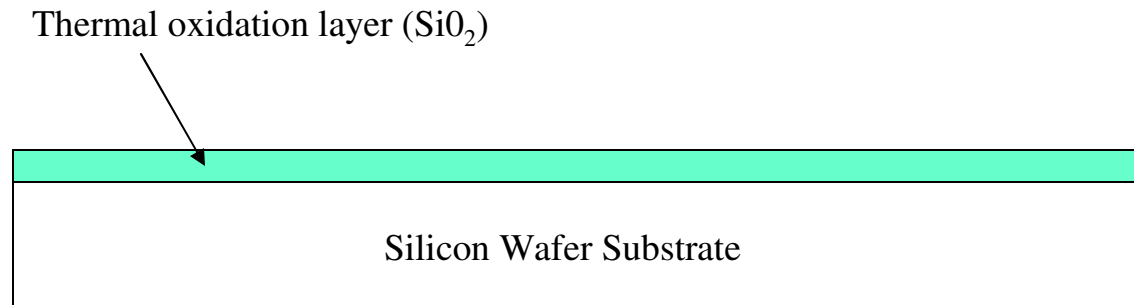
Silicon Wafers

- Silicon is grown as an “ingot” and then sawed into thin wafers
- Silicon ingots are grown in very clean environments to be free of electrical contaminants and physical defects
- Silicon wafers are produced in several diameters
 - The most common diameter in use today is 200mm (about 8 inches)
 - The next generation wafer diameter will be 300mm (about 12 inches)
- Typically, Semiconductor Manufacturers purchase semiconductor wafers from suppliers and do not make their own



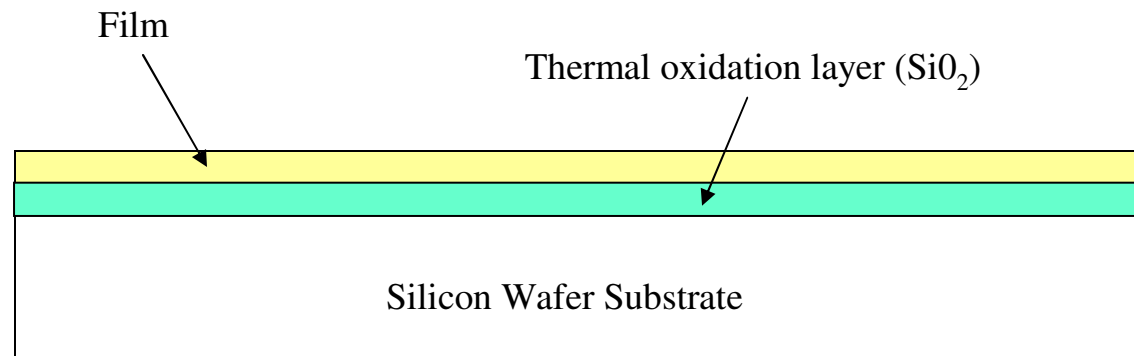
Oxidation

- When silicon is heated to a high temperature in an oxygen rich atmosphere it oxidizes
- Silicon oxide does not conduct electricity and so is used to isolate individual electrical circuits from each other on the wafer
- The thickness and density of silicon oxide layers is measured and controlled during the manufacturing process



Film Deposition

- Film Deposition is the process step where a layer of conductive or non-conductive material is deposited on top of the wafer
- The thickness and electrical properties of a film layer are measured and collected during the manufacturing process

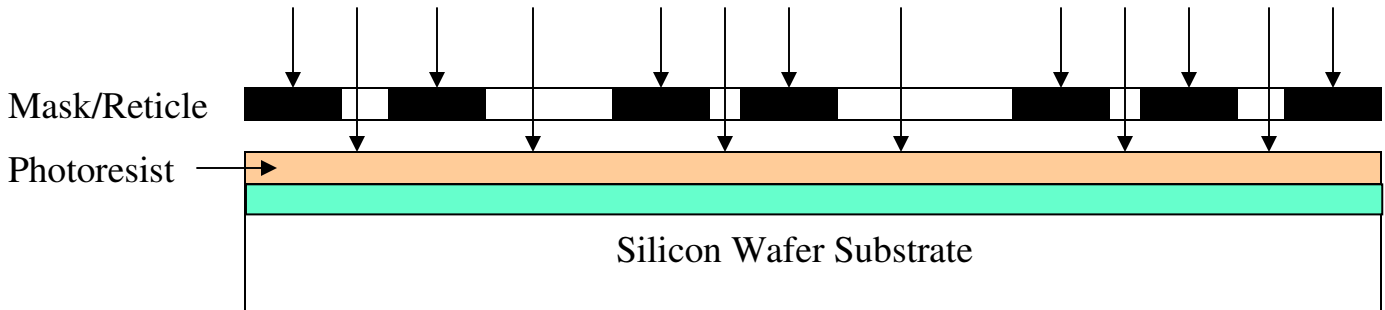


Photolithography (1/2)

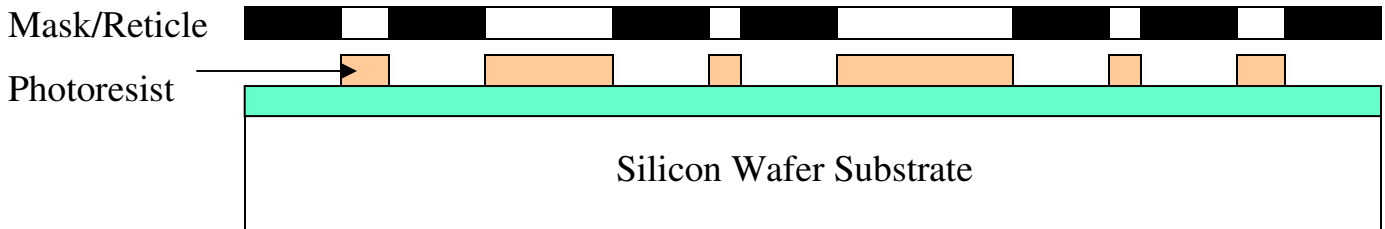
- Photolithography is the process step used to pattern a layer on a wafer
- Photolithography consists of applying photoresist on a wafer, exposing a circuit pattern using a mask or reticle, and developing the photoresist
 - Prior to the late 1980's the entire wafer was patterned at one time using a "mask"
 - A mask consists of all the individual integrated circuits to be patterned
 - In the late 1980's "step and repeat" photolithography was introduced
 - A small rectangular area is exposed using a "reticle", then the reticle is "stepped" (e.g. moved) to the next location
 - The exposure and step process is repeated until the entire wafer is patterned
- In either case, a mask or reticle consists of opaque and non-opaque patterns that block or allow ultra-violet light to strike the photoresist on the wafer, the light causes the photoresist to harden in the exposed areas
- "Developing" the photoresist causes the soft (un-exposed) photoresist to be removed and the hard (exposed) photoresist to remain on the wafer
- The dimensions of the developed photoresist layer are measured and collected during the manufacturing process

Photolithography (2/2)

Pre-Exposure:

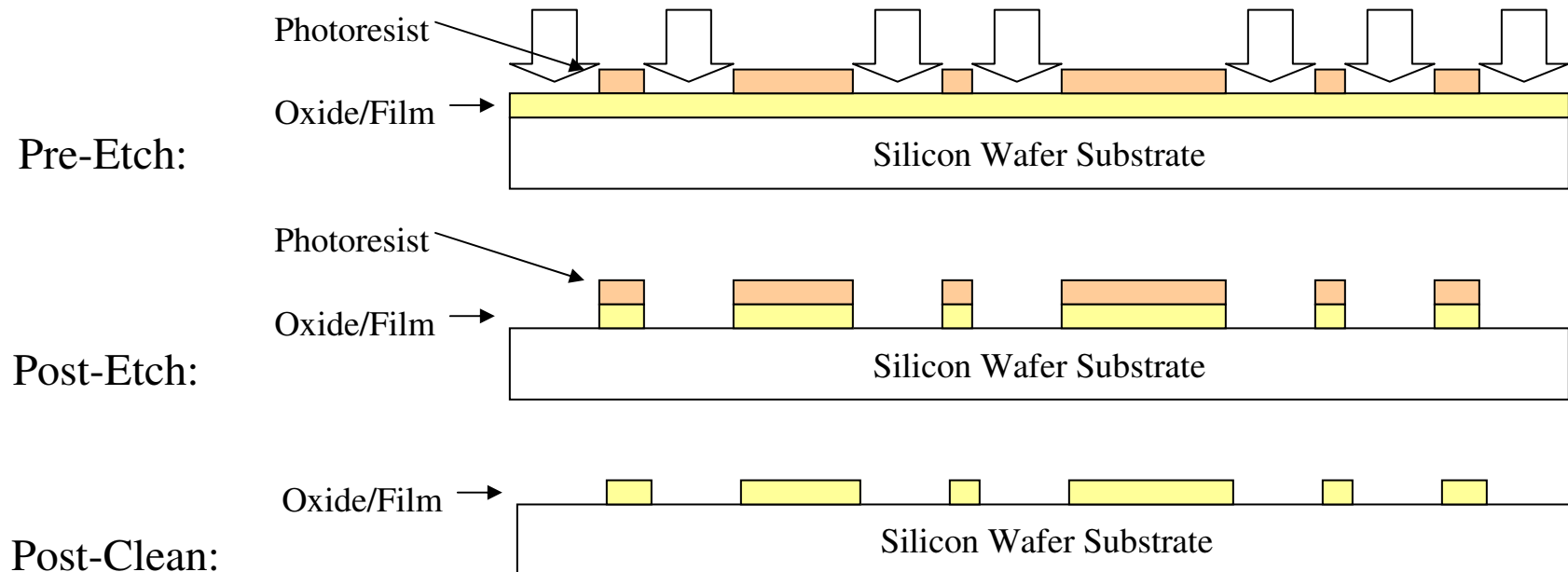


Post-Development:



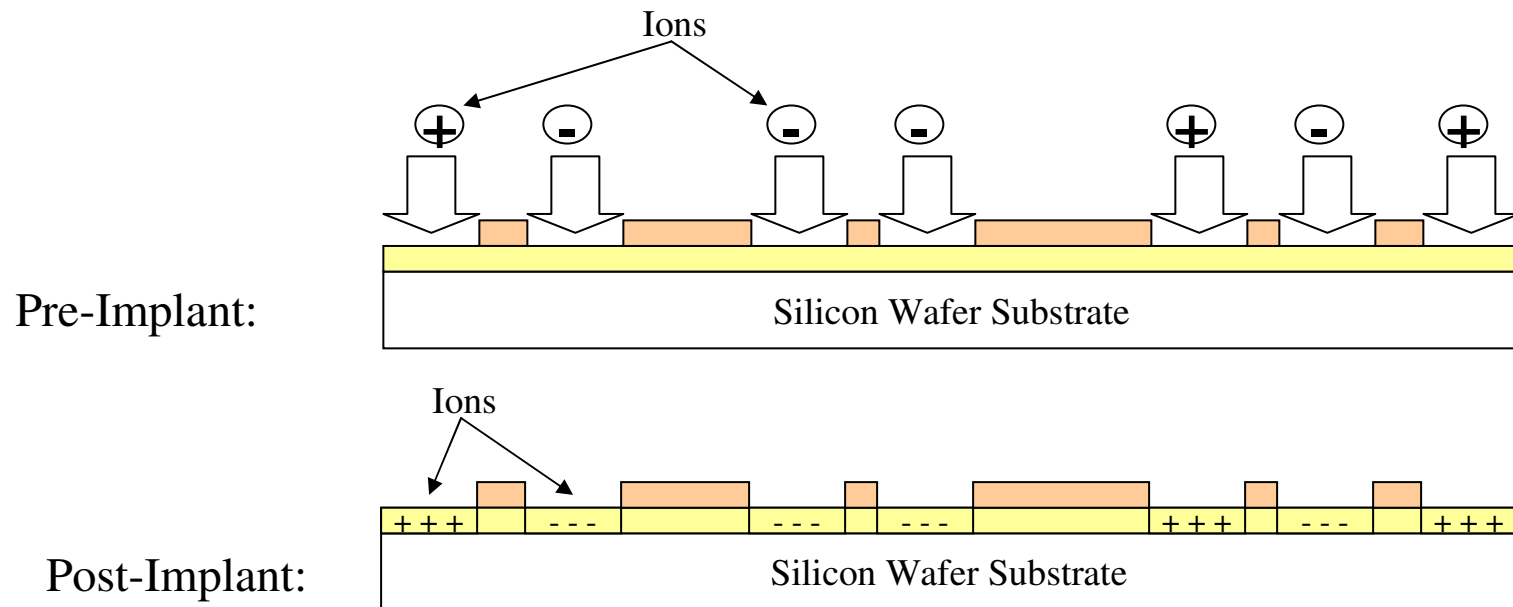
Etch

- Etch is the process step used to remove non-patterned oxide or film material after photolithography
- Machines called “plasma etchers” are used to remove the oxide or film not covered by photoresist
- After etch is complete, the photoresist is removed leaving only the patterned oxide or film on the wafer
- The dimensions of the etched layer are measured and collected during the manufacturing process



Implantation

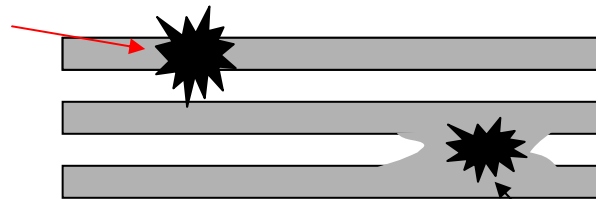
- Implant is the process step used to introduce controlled amounts of “dopants” into the semiconductor wafer
- Dopants are electrically active ions that are added to the wafer to modify the semiconductor properties of the wafer material
- Implantation can be done either before or after an etch step depending upon the desired results
- The electrical properties of a film layer after implantation are measured and collected during the manufacturing process



Wafer Fabrication Defect Inspection (1/2)

- Physical defects are introduced during the manufacturing process steps due to equipment and human problems
 - Is a particle of material that gets onto a wafer during processing
 - The defect particle can remain on the wafer or be removed during processing
- Defects can occur in many types and cause many different types of electrical and mechanical problems:
 - Can cause a patterned layer to be distorted at the site of the defect
 - Can remain trapped between layers resulting in mechanical stress within the circuit
 - Can cause electrical shorts or opens in a circuit layer or between layers
- Defects **CAN, BUT DO NOT ALWAYS**, cause circuit failures
 - Some defects are electrically and mechanically inert and cause no problem for the IC to function normally
 - Some defects can be dormant for long periods of time and then be activated later in the field which results in a “Customer Return” which is a Quality and Reliability problem

Defect causing an open circuit



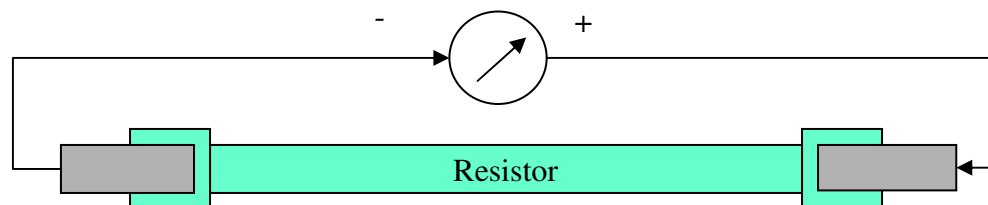
Defect causing a short

Wafer Fabrication Defect Inspection (2/2)

- Defects are identified by:
 - visual inspection during wafer fabrication
 - Inspection machines can automatically scan a wafer and photograph defects
 - Identified defects can be further analyzed using SEM, FIB, and other tools to determine the composition of the defect particle
 - electrical test during and after wafer fabrication
 - Defects can result in function failure during electrical testing
 - Memorys and some logic can be electrically “bitmapped” to identify the defect location

Parametric Test

- Integrated circuits are made up of smaller simple electrical components such as resistors, transistors, diodes, and capacitors
- Integrated circuits are designed to tolerate some amount of variation in the values of these simple components
- Electrical test structures are included on most wafers to measure representative sets of these simple components (typically located in the “scribe” lines that separate the die)
- The electrical results will vary due to normal variation in the wafer processing
- When the variation exceeds the “design limits” then the performance of the overall integrated circuit will not meet it’s specifications
- These simple components are tested both during and after wafer fabrication
- Parametric testing is performed using automated Test Systems and Wafer Probe Machines
- The electrical results, or “parametric results”, are critical to:
 - determining if process steps are operating within Statistical Process Control (SPC) limits
 - determining if the finished IC will perform to specification or not



Die Test

- Die Test is the first time that each Integrated Circuit on a wafer is tested to see if it meets the design specifications
- Testing is performed using automated Test Systems and Wafer Probe Machines
- Testing consists of measuring electrical characteristics such as:
 - Input and Output voltages
 - Operating and standby currents
 - Specific signal timing
 - Frequency of operation
 - Operational logic
- If an Integrated Circuit...
 - passes all of the tests it is called a “pass”, “good”, or “Spec” die
 - fails one or more tests then it is called a “fail” or “non-functional” die
- After a die is tested it is “binned” out
 - Binning associates a unique code for each type of passing or failing die
 - “Hard” bins refers to bin schemes that are fixed by the test system or software
 - “Soft” bins refers to bin schemes that are defined by the test engineer
 - Soft bins allow more levels of identifying of the reason that a die passed or failed during testing
- Die Test is performed at one or more controlled temperatures
- Die Test produces an enormous amount of data for each die on each wafer!
- The die test results are critical to:
 - determining if the finished IC will perform to specification or not

Die Repair

- Many complex integrated circuits have some degree of memory and/or logic redundancy designed into the integrated circuit
- If the die fails die test, redundancy allows memory and/or logic circuitry to be replaced with the spare or “redundant” circuitry
- Redundant circuit repair can be performed with automated electrical or laser techniques depending upon the design of the repair circuitry
- Die test is performed again after repair to determine if the die is now working to specification using the the redundant circuitry
- Redundancy and repair are critical for large area memory and logic devices to improve the die yield of a wafer

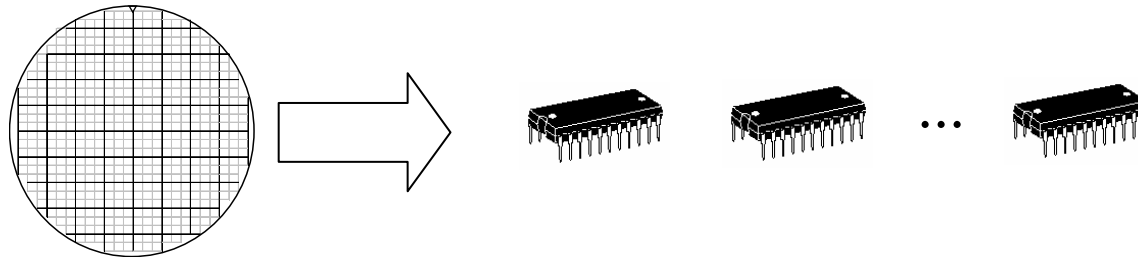
Wafer Fabrication Yield

- The overall wafer fabrication yield is the product of all of the test and inspection steps causing wafers and die to be identified as bad
- During wafer fabrication entire wafers are often “scrapped” if a test or inspection step determines that the cause of failure is severe enough to impact most of the die on the wafer
- **Process Yield**
 - refers to the number of wafers that complete wafer fabrication to the number of wafers that started wafer fabrication
 - This includes wafers lost due to handling, parametric, and defect problems
- **Wafer Yield**
 - refers to the number of good die after die test to the number of die on a wafer

$$Y_{WF} = Y_{Process} * Y_{Die\ Test}$$

Assembly

- Assembly is the process of converting wafers into individually packaged integrated circuits
- The assembly process consists of
 - sawing the wafer between die
 - putting each die into a package
 - bonding the die pads to the packages leads
 - sealing the package
 - printing identification markings on the package
- Assembly is a mix of manual and automated processes that are very physically stressful to the individual integrated circuits.
- A packaged die is referred to as a “chip” or “unit”
- Some chips are physically damaged as a result of the assembly processes and are visually identified and scrapped after assembly
- **Assembly Yield**
 - Is the ratio of the number of chips out of assembly to the number of good die into assembly



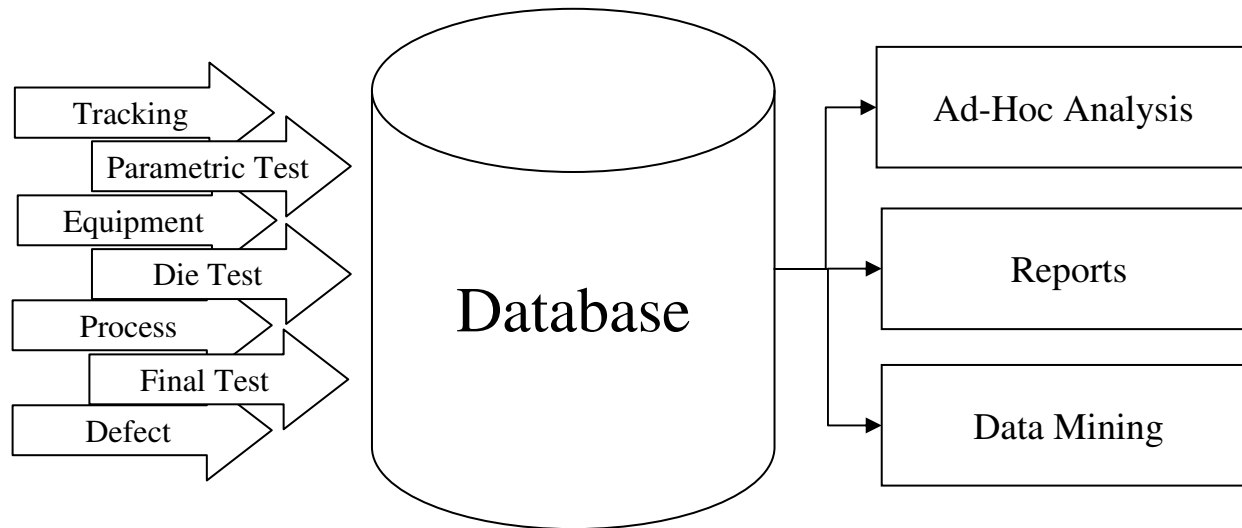
Final Test

- Final Test is the process of testing the packaged integrated circuits, chips, to specification
- Final Test consists of multiple test insertions of each chip at different temperatures, voltages, and frequency of operation in an attempt to duplicate extreme conditions in a real world environment
 - Final Test is the true measure of a chips performance
- In addition to the final test of each unit, samples are pulled from each group of units for Quality Assurance testing
 - Quality Assurance testing is a double check to verify that the production final test was performed correctly
- Overall **Final Test Yield** is the product of the yields of each of the final test steps

$$Y_{FT} = Y_{FT1} * Y_{FT2} * \dots * Y_{FTn}$$

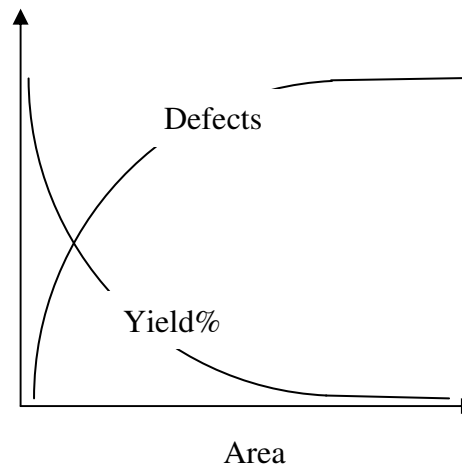
Engineering Data Analysis Systems

- An enormous volume of data is measured and collected throughout the Semiconductor Manufacturing steps and collected into one or more databases
- Engineers can then utilize statistical data analysis software to analyze this data
- Analyzing the many different types of semiconductor manufacturing data requires that the Analyst have highly specialized knowledge of the design, process, product, and testing to interpret the data correctly
- Most Semiconductor Manufacturers buy or build software systems to automated the collection, storage, access, and analysis of their manufacturing data
- Ideally, an Engineering Data Analysis system should contain all of the tracking, equipment, process, defect, parametric test, die test, and final test data so that it can be correlated, analyzed, and reported



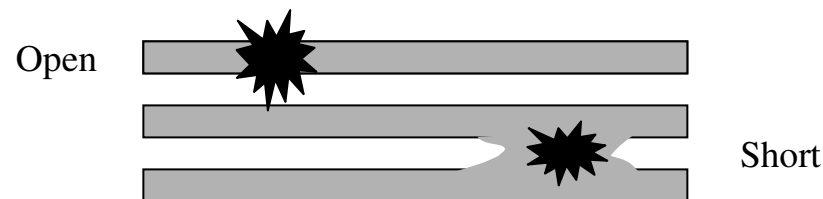
Defect Engineering (1/2)

- All wafers have defects!
- Defects are distributed both randomly and systematically on a wafer
- The number of randomly distributed defects increases exponentially per unit of area, thus the yield decreases exponentially per unit of area
- Defect Engineers work to identify which defects are “killers” (that result in a bad die) and which are benign (do not cause bad die)
 - Wafers with killer defects are usually scrapped during wafer fabrication
 - Wafers with benign defects are sent on to die test from wafer fabrication
- More importantly, Defect Engineers work to identify the process and equipment causing the defects so that the Process Engineers can stop the defects from being created in the first place.



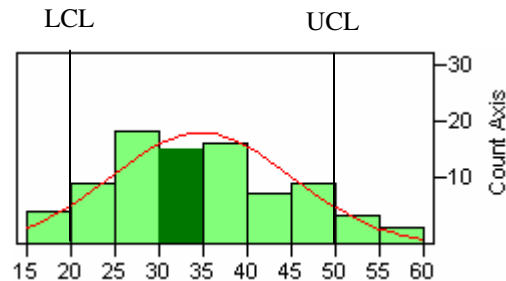
Defect Engineering (2/2)

- The objective of the Defect Engineer is to minimize the number of defects per unit area and thus increase the yield
- The identification of “killer” defects is accomplished by comparing the die test yield to the defect counts per layer on the same wafers for a statistically significant sample of wafers with die of different areas a correlation between defect count and yield can then be established using statistical regression techniques
 - The identification of killer defects can be further understood by correlating to individual hard and soft bin yields to identify the specific die failure mode that the killer defect causes
 - Often killer defect analysis using production die test data is futile because the defect may be electrically benign at the die test temperature but electrically active at another temperature
 - To comprehensively correlate killer defects requires die test or final test data over several temperature and voltage ranges
 - Final test data is only useful if both bad and good die are assembled and the final test chips can be identified with their wafer and die location at die test



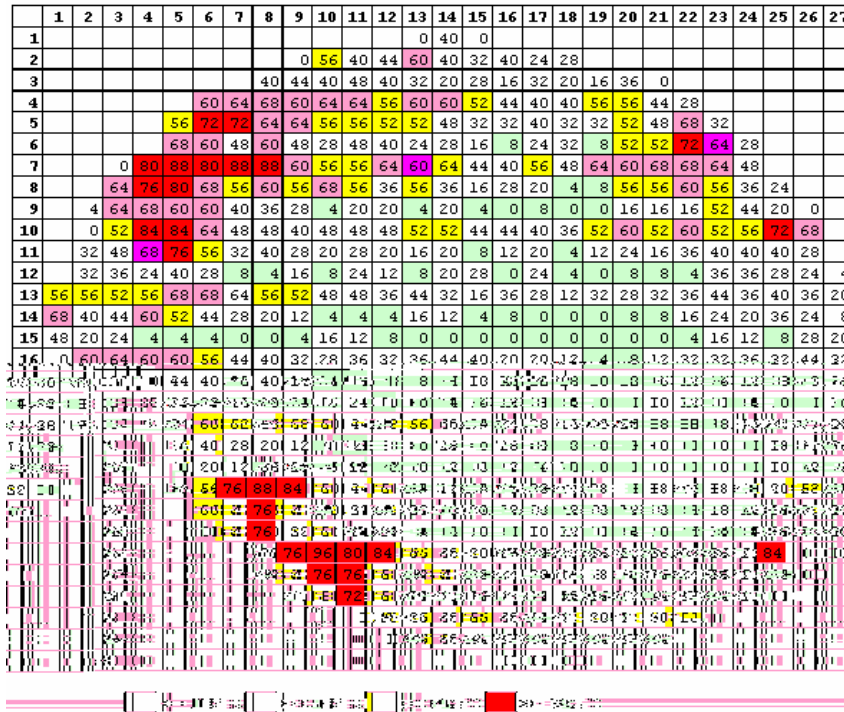
Device Engineering (1/2)

- The role of the Device Engineering is to monitor the parametric test results for the simple semiconductor devices, identify parameters not within specification, and then work with the appropriate process engineer to resolve the problem.
- The Device Engineer must review data on 10's to 100's of simple semiconductor devices and establish correlation's to die test yield and process SPC metrics.
- Device Engineers use ad-hoc statistical data analysis software tools and automated reports to help them identify yield problems
- Two of the most commonly used statistical analysis techniques used by Device Engineers are “distribution plots” and “wafermaps”
- Distribution plots are a graph of the frequency of occurrence of a measured parameter.
 - The most typical type of distribution is a “normal” distribution.
 - The distribution plot tells the Device Engineer how many of the parameter readings are “in control” (between the LCL and UCL lines) and how many are out of control (left of LCL and right of UCL)
 - The out of control values indicate that the simple semiconductor devices will not perform to specification which means that the integrated circuit may not perform to specification



Product Engineering

- The role of the Product Engineer is to monitor the die and final test results to make sure that the integrated circuit is performing to specification
- Product Engineers work to establish correlation between die and final test results
- Product Engineers also use ad-hoc statistical data analysis software tools and automated reports to help them identify yield problems
- Product Engineers also work very closely with the Circuit Designers to make sure that the integrated circuit functions as the Designers intended it to

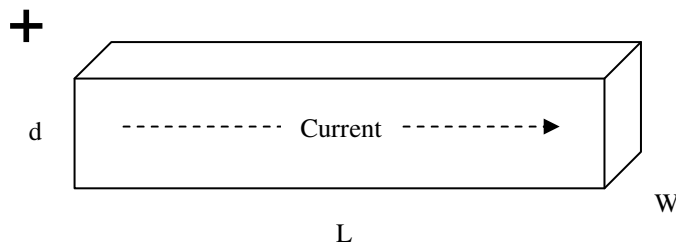


Test Engineering

- Test Engineers write the test programs used by the Automated Test Equipment (ATE) to perform the testing
- Test Engineers specialize in parametric, die, and final test areas
- Test Engineers work closely with the Device and Product Engineers to develop and improve the test programs

Resistor Characteristics

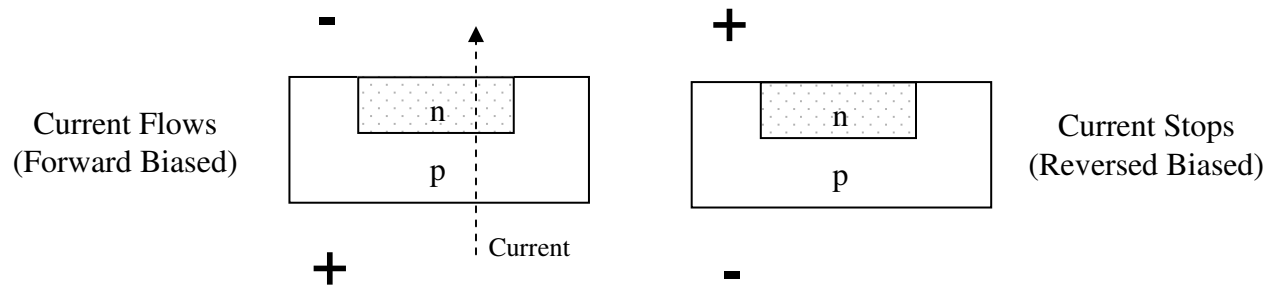
- A simple resistor
 - is a device that opposes the flow of current
 - is created by “doping” a well defined area of silicon
- Doping is the process of introducing atoms and/or ions through implantation that modify the electrical characteristics of the material being doped
- Doping creates a three dimensional volume that has a different and the desired resistance value compared to the surrounding silicon area
- When a voltage is applied across the length of the resistor a current flows from the positive to the negative terminal of the voltage source
 - The resistance (R) is equal to the voltage (V) divided by the current (I)
 - Semiconductor resistors are geometrical and so the resistance (R) is also equal to the sheet resistivity (Rs) times the length (L) divided by the width (W) of the resistor



$$R = \frac{V}{I} = \frac{R_s * L}{W}$$

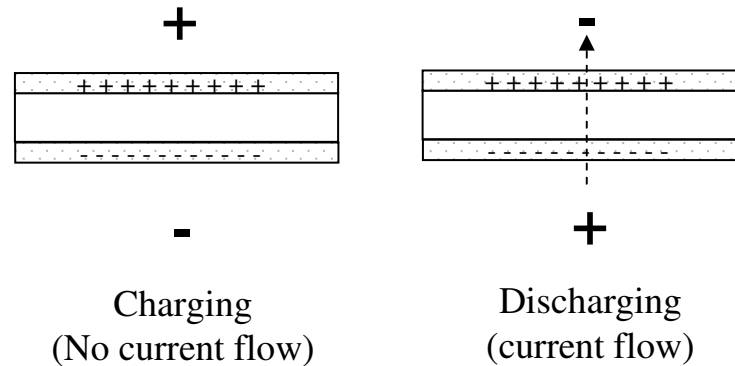
Diode Characteristics

- A simple diode:
 - is a device that allows current to flow in one direction
 - is created by “doping” a well defined area of silicon with the opposite type of dopant atoms or ions
 - “positive” or “p-type” dopants are Boron, Aluminium, Gallium
 - “negative” or “n-type” dopants are Phosphorus, Arsenic, Antimony
- When a voltage is applied across the diode so that the negative (-) terminal is applied to the n-type silicon and the positive (+) terminal is applied to the p-type silicon then a current will flow from the n to the p region
 - This is called the “forward biased” region of operation
- When voltage is applied so that the voltage polarity is the opposite of the material polarity then no current flows
 - This is called the “reverse biased” region of operation
- Diodes are used to switch the flow of current on and off in an electrical circuit



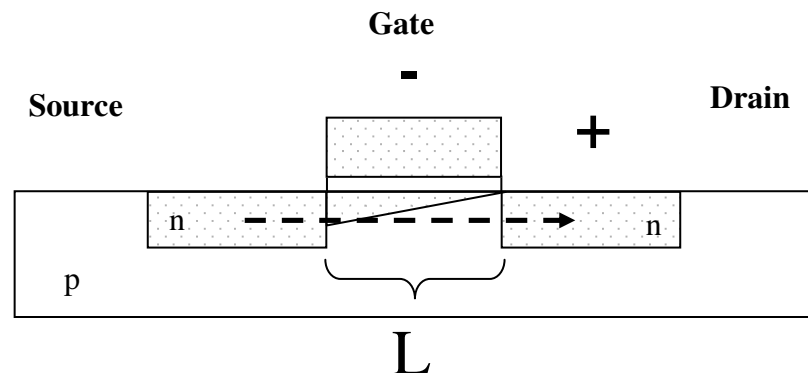
Capacitor Characteristics

- A simple capacitor
 - is a device that stores electrical charge
 - is created by two conducting materials separated by a non-conducting material
 - the amount of charge that a capacitor can store is inversely proportional to the thickness of the non-conducting, or dielectric, region
- Capacitors store charge when voltage is applied in one direction and then discharge their charge when the voltage across the capacitor is reversed
 - when a capacitor is storing charge it is also blocking the flow of current through it
 - when a capacitor discharges it supplies its charge and creates a current flow



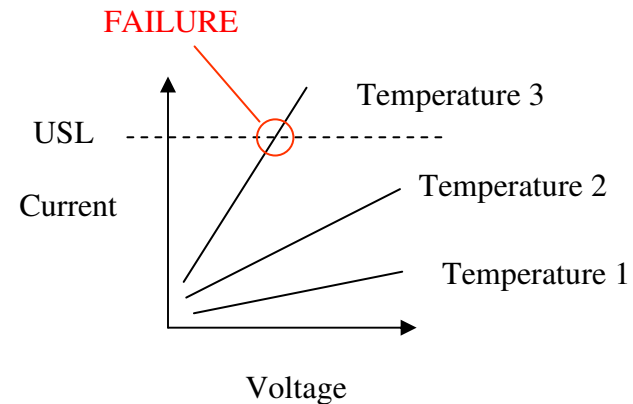
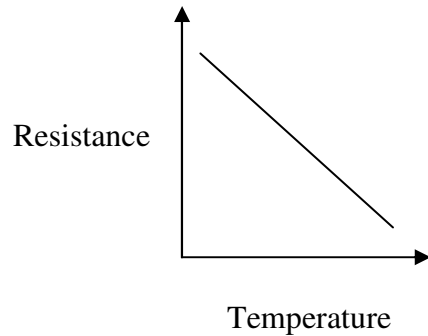
MOS Transistor Characteristics

- A simple MOS Transistor is
 - a combination of two diodes and a capacitor
 - acts as a valve to control the amount of current flow in an electrical circuit
- One diode is called the “Source”, the other diode the “Drain”, and the capacitor between the Source and Drain is called the “Gate”
- As the voltage applied to the Gate is varied the amount of current flowing from the Source to the Drain is varied proportionately
- MOS Transistors form the basis for making complex logic and analog electrical circuits
- The area under the Gate is called the “channel” and the length of the channel (L) is VERY critical to the transistors performance
 - The shorter the channel length the faster the device will conduct current



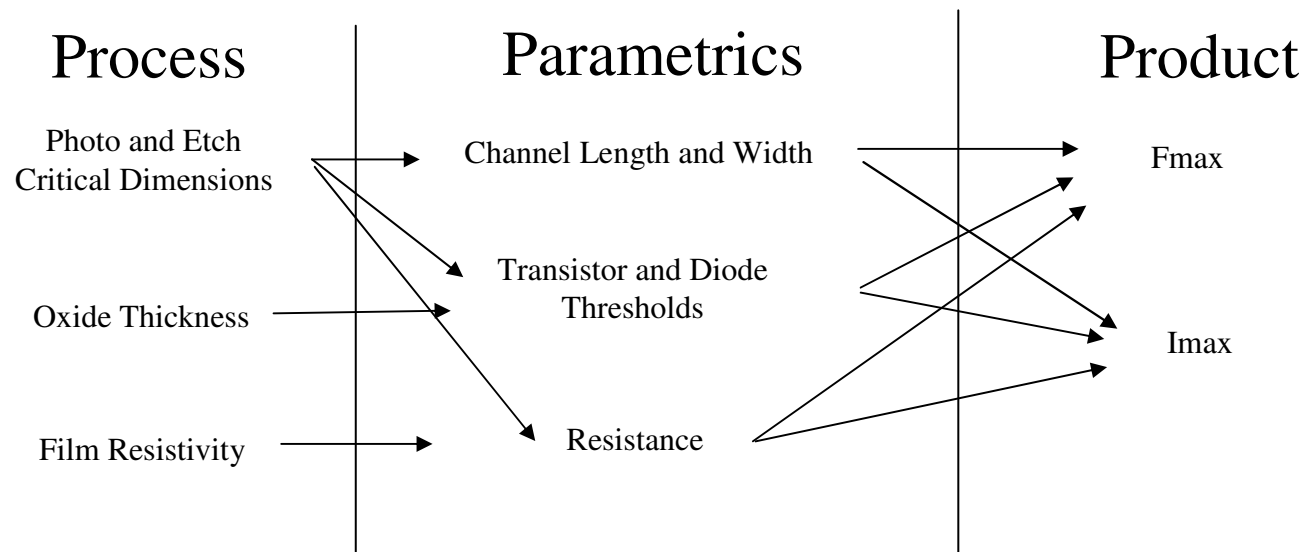
Operating Temperature Effects

- All semiconductor materials have different electrical characteristics at different operating temperatures
 - In general, the resistance of most semiconductor materials decreases as temperature increases
 - Therefore, for a constant voltage the current flow increases
 - However, for diodes and MOS transistors the “off” state current increases with decreasing temperature
- The net result of temperature effects on a die or chip can dramatically change its operating characteristics over a given temperature range
- Integrated Circuits have specifications for maximum and minimum operating voltages, currents, and frequencies at specific temperature ranges



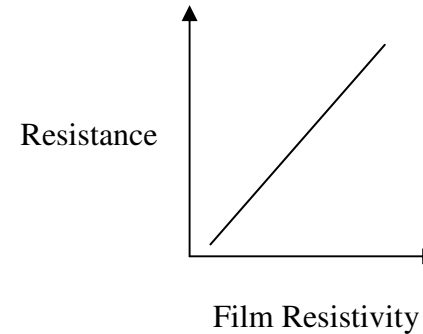
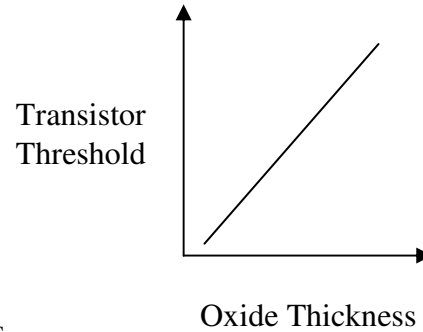
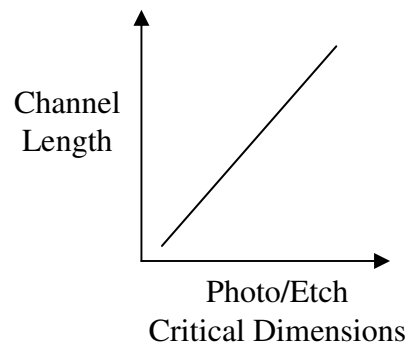
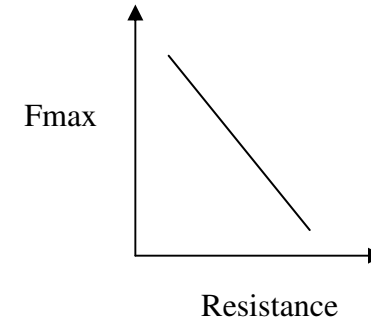
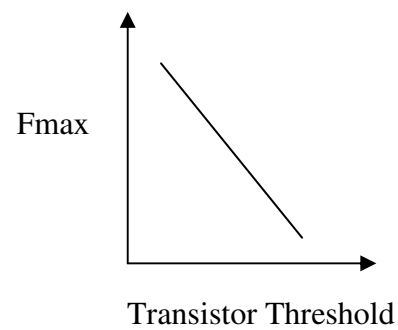
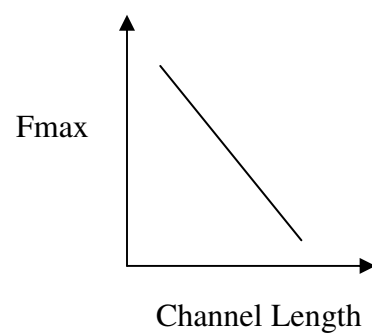
Operating Frequency and Current Analysis (1/2)

- One of the key metrics of an integrated circuit is its operating frequency
- The operating frequency is determined by the net result of the speed of all of the simple components in the integrated circuit
- Lower resistances and short transistor channel lengths allow circuits to perform faster but also consume more current
- Using Engineering Data Analysis software systems and statistical analysis techniques allows an Engineering to quantitatively understand the cumulative effects of processing, to simple devices, to final test results
- For example, the maximum frequency (F_{max}) and current (I_{max}) of operation of a microprocessor is determined by



Operating Frequency and Current Analysis (2/2)

- The Device or Product Engineer could perform the following regressions analysis to understand the primary and secondary relationships of these parameters



Standby Current Analysis

- Another key metric of an integrated circuit is “standby current”
 - is determined by the amount of current flowing when the IC is in its lowest current state
 - Often, due to the characteristics of transistors and other materials in low current states of operation, the amount of standby current increases with decreasing temperature
 - Lower resistances and short transistor channel lengths cause circuits to consume more current

