VLSI Test Technology and Reliability

Lecture 10(2)

Semiconductor Reliability

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Learning aims

- Realize the importance of reliability
- Describe reliability failure mechanisms
- How to measure reliability
- Future reliability challenges

Contents

- Concepts and definitions
- Motivations
- Semiconductor reliability
- Failure mechanisms
- Reliability testing
- Future challenges and summary

Concepts and definitions

Design, manufacturing, and test

Operational life

Wearout

Quality

- Guarantee that the IC performs its function at t=0
  time-independent
- Driven by
  defect/fault during manufacturing

Reliability

- Guarantee that the IC performs its function for $0 \geq t \geq$ lifetime
- Meeting specification over time
  time-dependent
- Driven by
  changing material properties, application profile, environment.

Reliability moves farther than Quality

Motivations

- People Life
  - Reliable products save people in
    - Highway travelling
    - Air travel
    - Life critical medical procedures
- Customer Satisfaction
  - Reliability effects future business
    - Iphone satisfied 82% of users
    - 16% of them bought Iphone in next 6 months
- Competitiveness Advantage
  - Reliable companies get greater market share
    - Apple got 20% additional market in US than Asus
    - Apple scored reliability 365 as compared to Asus 305

Motivation……………

- Challenger (1986)
  - Exploded after 73 seconds of liftoff
  - Failing of O-ring seal in solid rocket booster
- Concord 4590 (2001)
  - Reliability checks were ignored

The entire crew and passengers died

Customer satisfaction……………….

- Honda vs. Yogu
- Yogu ignored reliability
  - The car is named Yugo, because it doesn't….
- Toyota downfall 2010
  - Ignored reliability of the break pedals
  - Lost 2 billion dollars

Business is lost

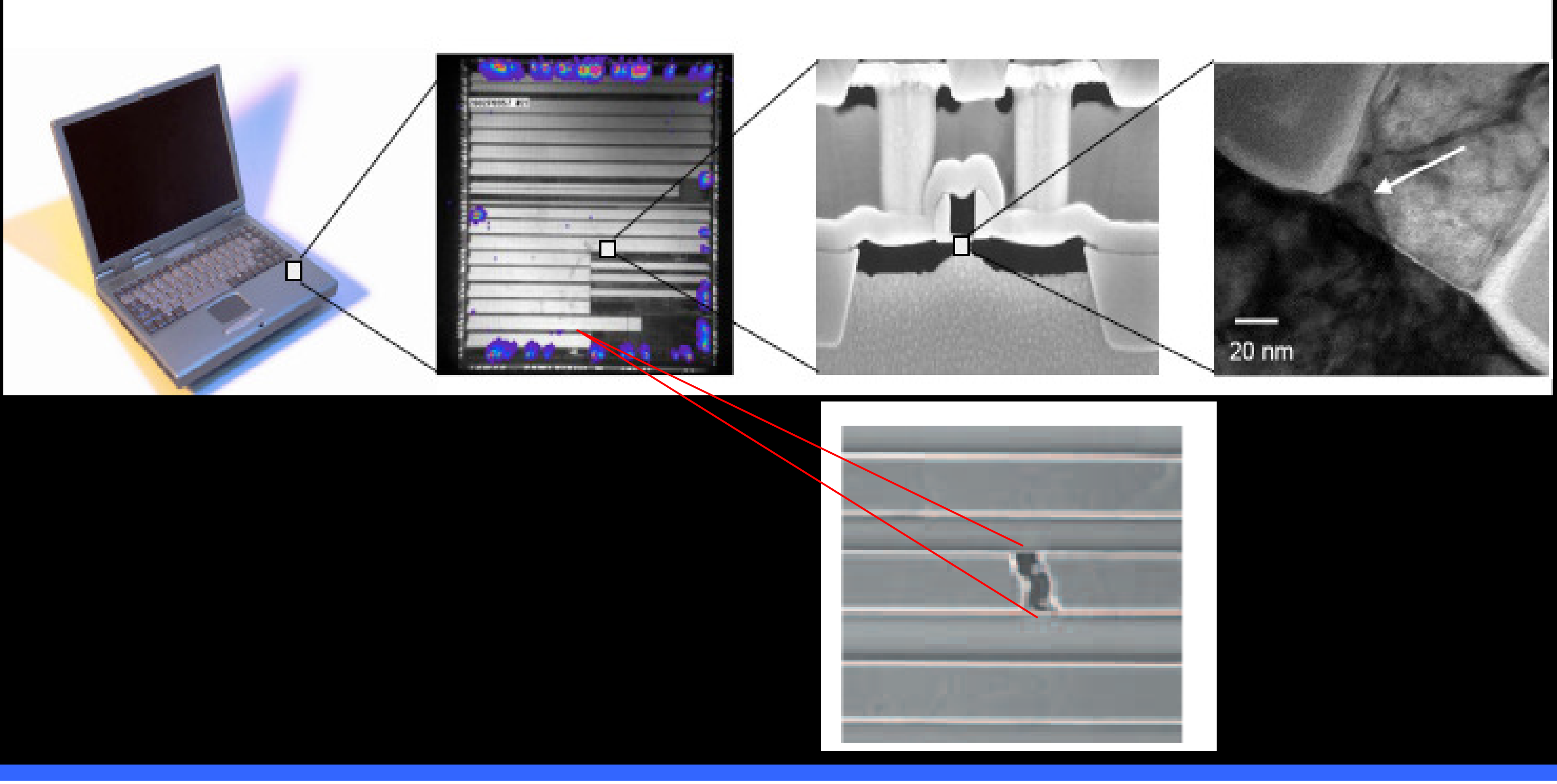
Competitiveness advantage… ~~Reliability~~

- Intel's 820 Chipset Delayed
  - Focused on design but avoided reliability analysis
  - Officials reported that delay is due to reliability issues in 820 chipset

First to enter market, first to leave

Semiconductor reliability

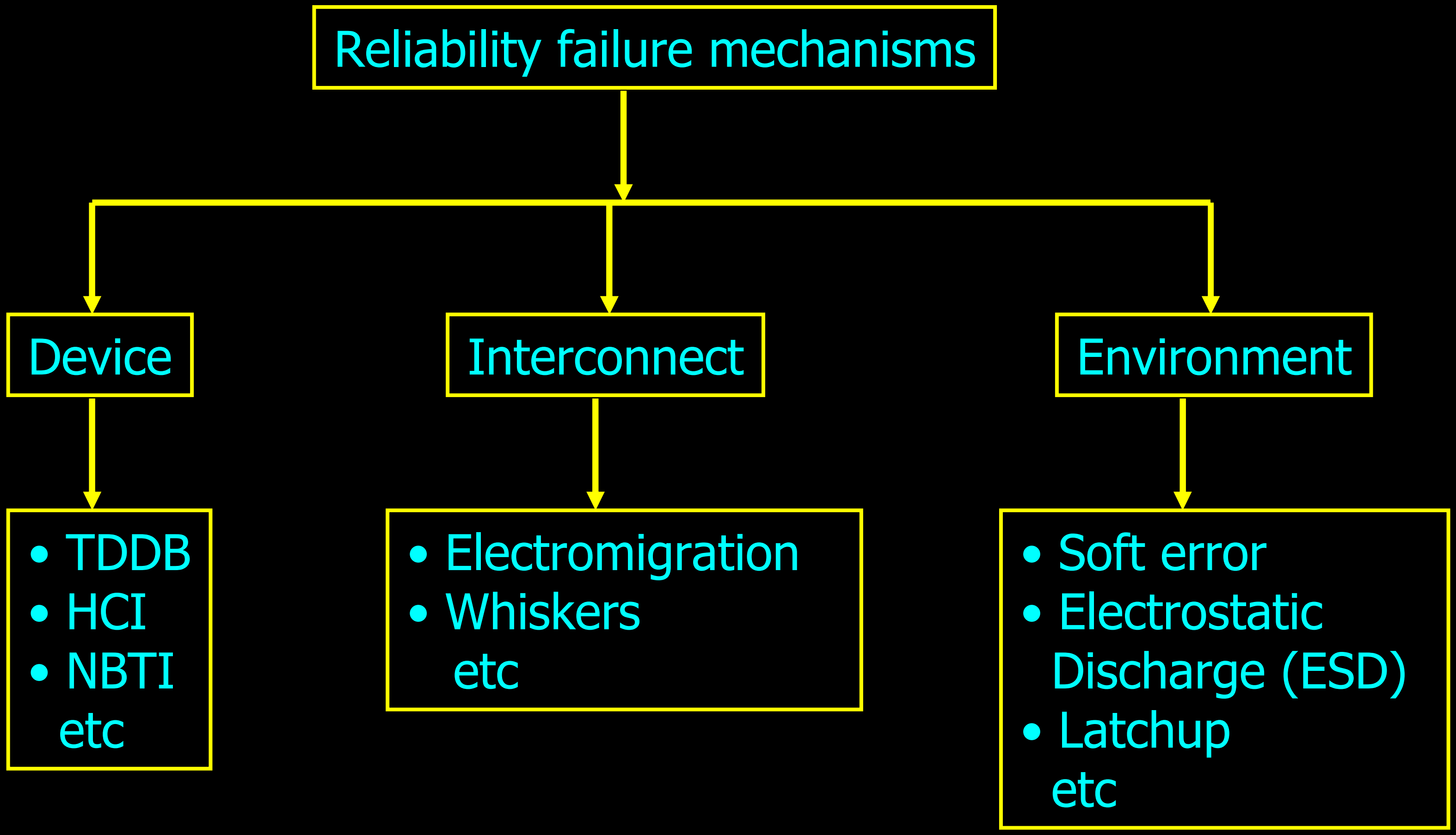
- IC turns on trillion of times in harsh condition during lifetime
- A manufacture bits the company on reliability physics



Semiconductor reliability………… Failures

- Reliability failure results in
  - Functional failure
    - Permanent
    - Temporary
  - Structural damage
- Failure sources
  - Semiconductor doping
  - Temperature
  - Radiation
  - Electric field
  - …………

Reliability failure mechanisms… Classification



Reliability failure mechanisms

- Device
  - TDDB
  - HCI
  - NBTI

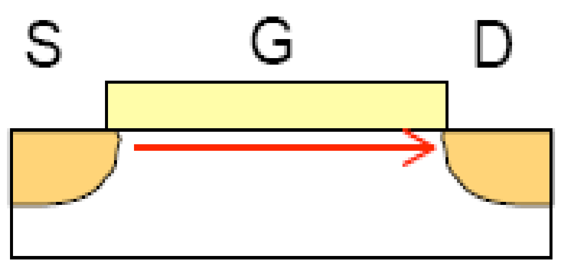
  etc
- Interconnect
  - Electromigration
  - Whiskers

  etc
- Environment
  - Soft error
  - Electrostatic Discharge (ESD)
  - Latchup

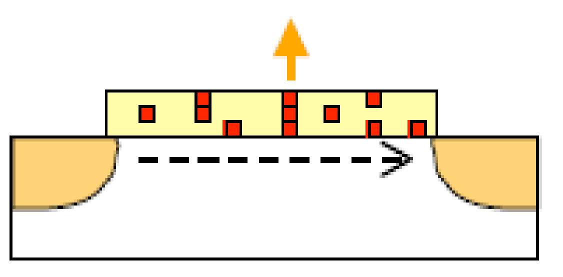
  etc

Device failure mechanisms

- Gate oxide degrade with the passage of time due to breaking of bonds
- Broken Si-H bonds
  - PMOS:
    - Negative Bias Temperature Instability (NBTI)
  - NMOS:
    - Hot carrier degradation (HCI)
- Broken Si-O bonds
  - Time Dependent Dielectric Breakdown (TDDB)



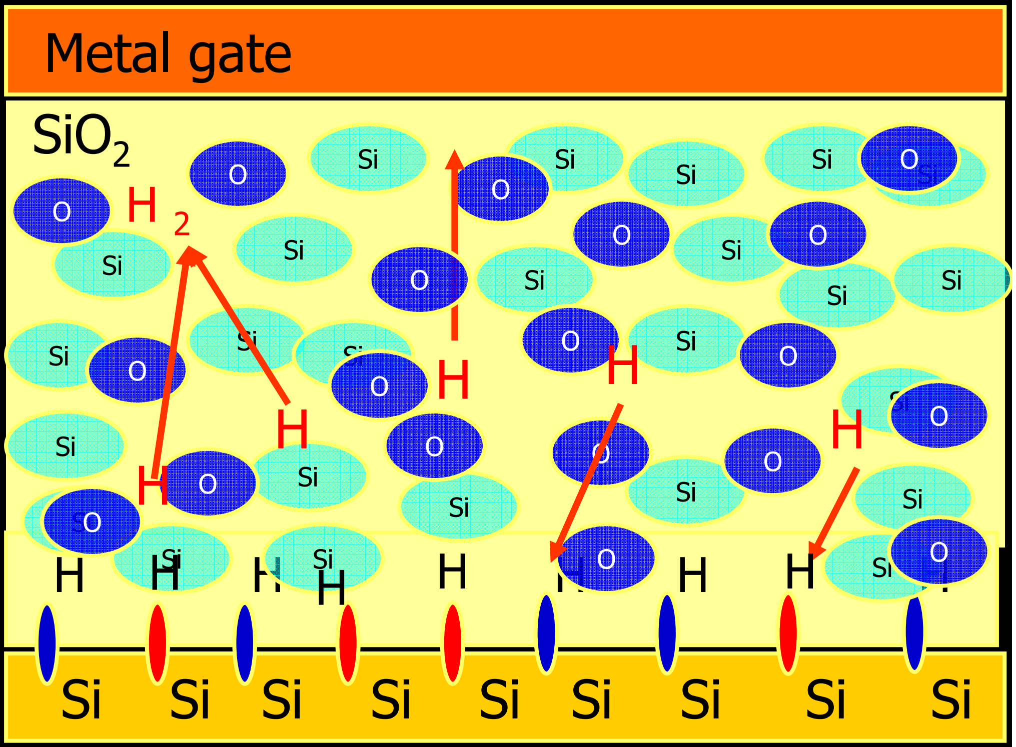
Initially



After some time

Device failures …………………. NBTI

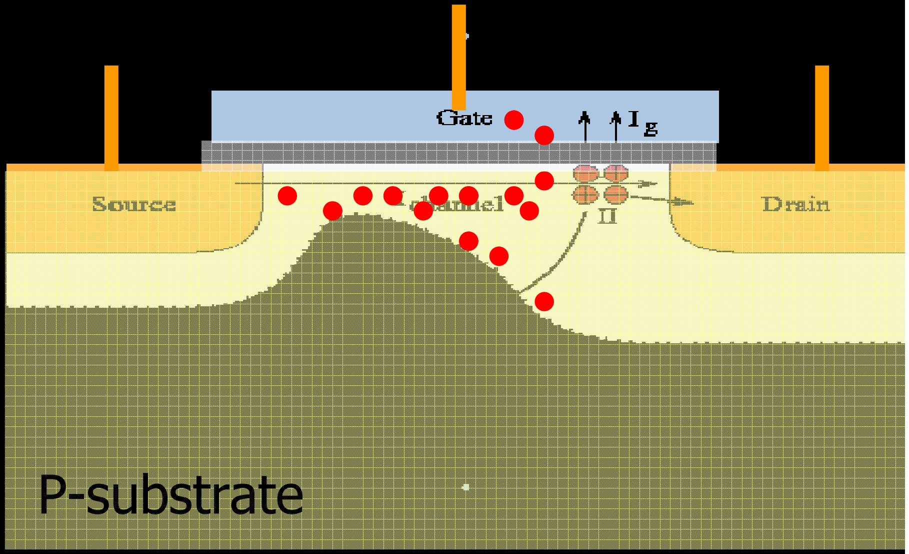
- NBTI degrades PMOS transistor at
  - Negative gate potential
  - Elevated temperature
- The gate potential breaks Si-H bonds and create positive charges at the interface
- The charges effect the threshold voltage, disrupting device characteristics
- Self annealing
- After-effects
  - Threshold voltage increases
  - Drain current decreases



High Electric field and Temperature enhances NBTI

Device failures ………………… HCI

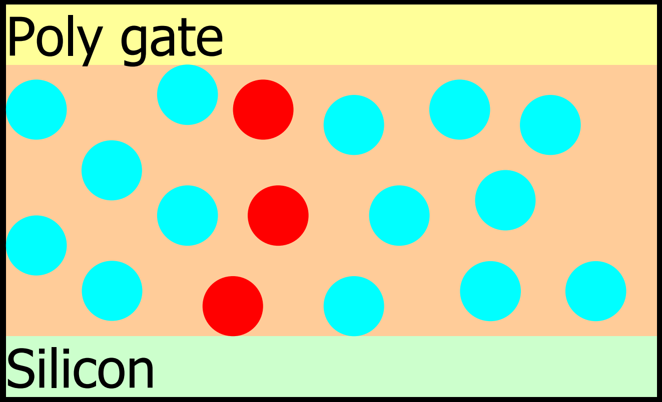
- HCI affects NMOS transistor
- Channel carriers get energy by impact ionization
- Most of the carriers are collected at the drains, but some are directed toward gate or substrate
- Energetic carriers breaks bonds in
  - Gate oxide
  - Silicon substrate
- After-effects
  - Threshold voltage increases
  - Saturation current decreases
  - Leakage current increases



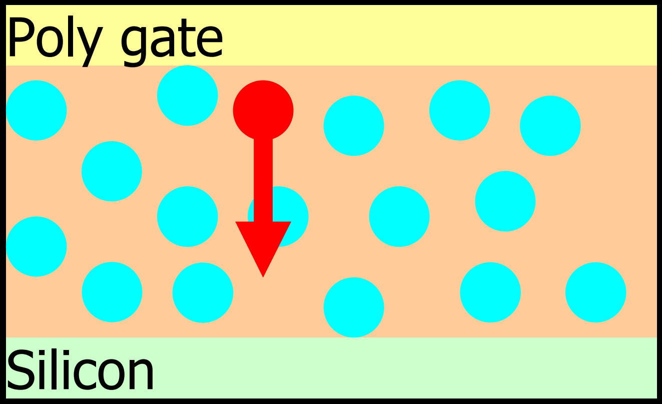
High carrier velocities and short channel enhances HCI

Device failures ………………… TDDB

- TDDB affects both PMOS and NMOS transistors
- Gate dielectric suffers from short circuit
- Percolation current
  - With the passage of time charges inside gate oxide align and result in a continuous path
- Direct tunnelling
  - Charges jumps directly across the oxide layer
- After-effects
  - Loss of gate voltage control
  - Increase in gate current



Percolation current

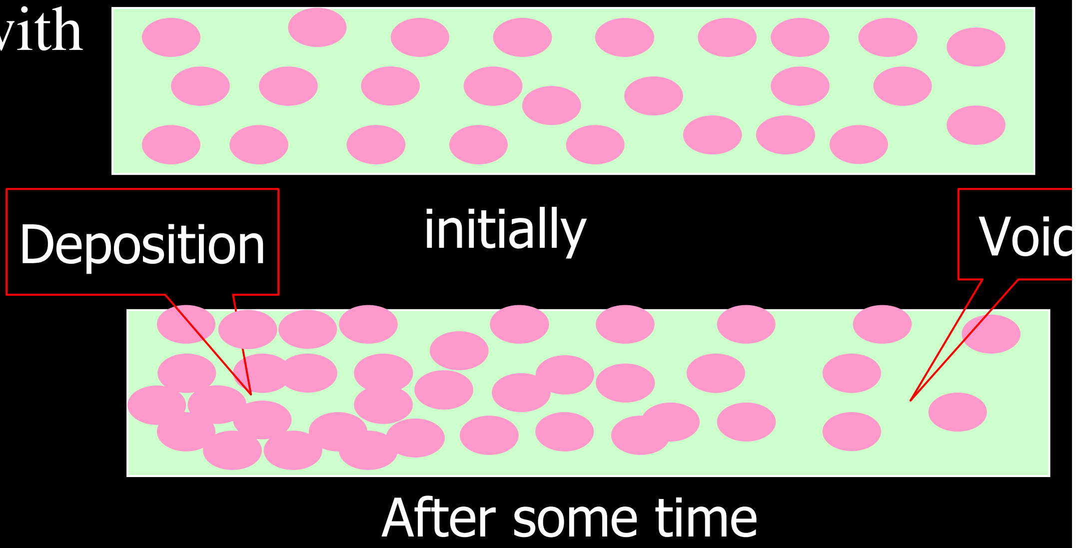


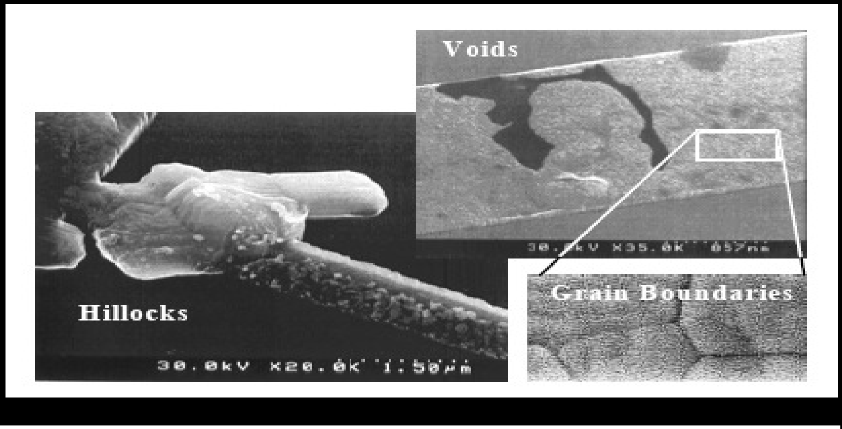
Direct tunneling

High temperature, thin oxides and high field enhances TDDB

Interconnect failures…… Electromigration (EM)

- EM affects interconnects and bondings
- Interconnect atoms migrate with electrons due to
  - Field force
  - Momentum exchange
- After-effects
  - Void formation
    - High resistance
    - Open circuits
  - Deposition
    - Small resistance
    - Short circuits

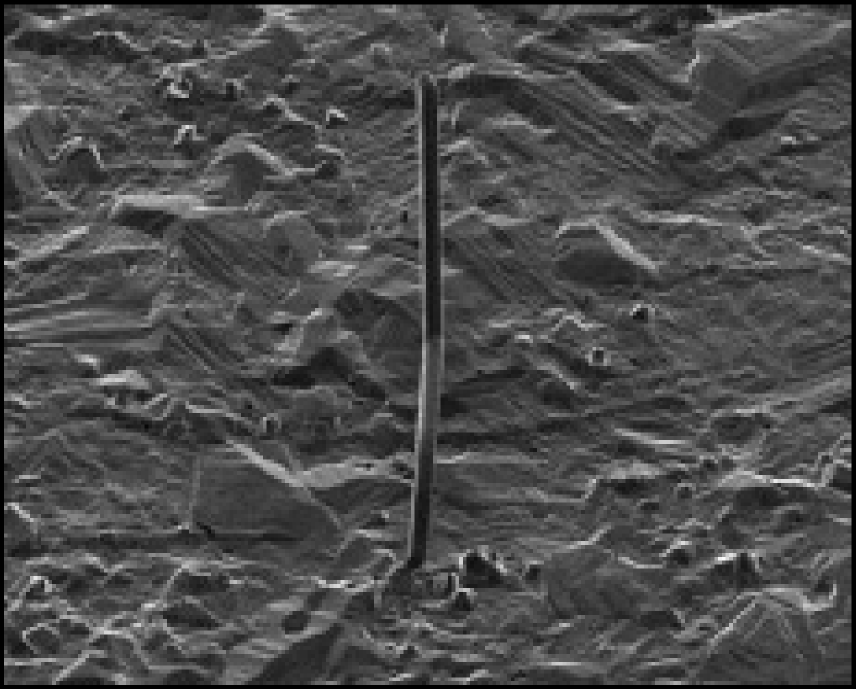




EM accelerates with shrinking interconnects and current density

Interconnect failures…… ……… Whiskers

- Whiskers affects interconnect joints
- Needle like protrusion at joint that result from
  - Diffusion effect
  - Re-crystallization
- After-effects
  - Electrical shorts
  - Antenna in high frequency applications

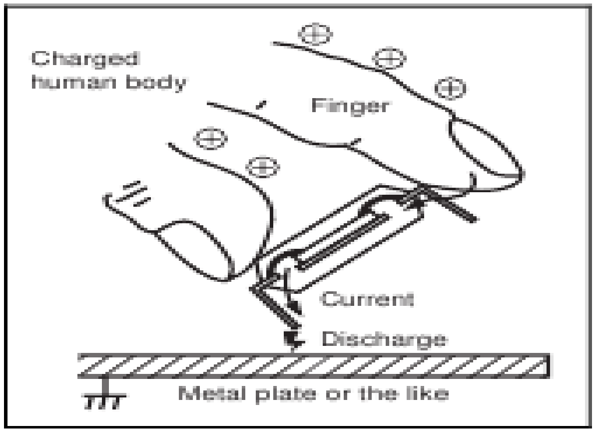


A thin whisker about 300nm long

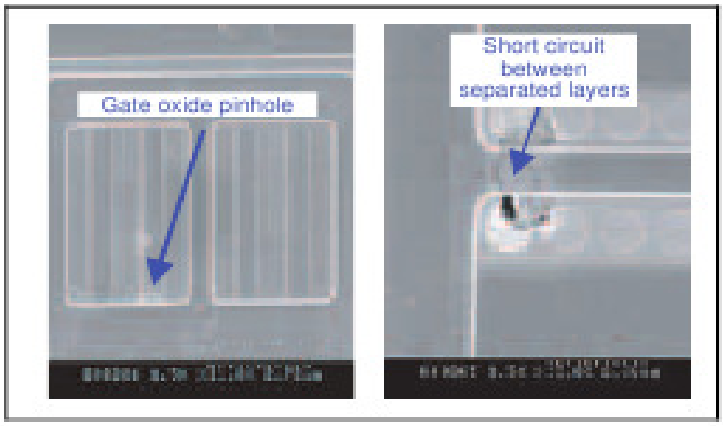
Whisker growth will accelerate due to ban on using lead (Pb)

Environmental failures……………ESD

- ESD is common phenomena observed by rubbing two object that creates charges
- ESD damages gate oxide due to
  - Static charges.
  - Switching transient
  - EM pulses
- Sources of charges
  - Human body
  - Manufacturing machines
  - Charged devices
- After-effects
  - Transistor junctions burnout
  - Metallization burnout



Discharge Model with Human Body

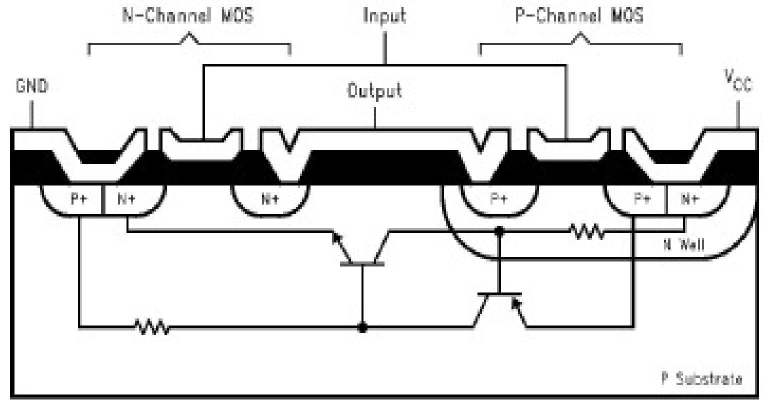


ESD Damage

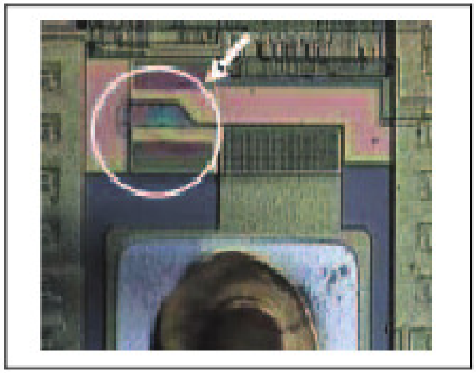
ESD accelerates with scaling coz sources are constant

Latchup

- Latcup affects both PMOS and NMOS
- Latchup ignites parasitic BJT's in CMOS due to
  - Supply voltage over/undershoot
  - External charges
- The cross coupled BJTs have positive feedback that shorts the internal CMOS junctions
- After-effects
  - Excessive drive currents
  - Function failure
  - Device burnout



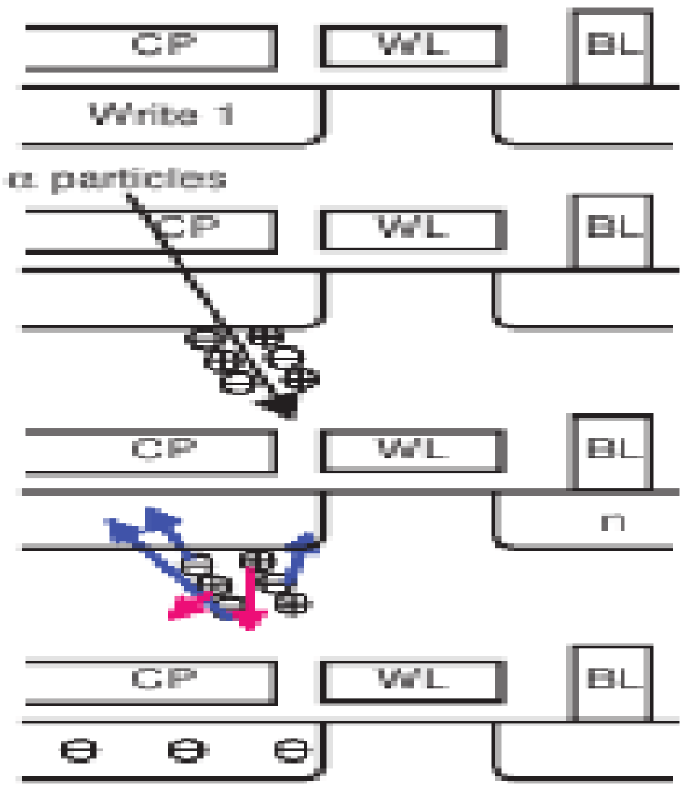
Cross Section of CMOS Inverter and Parasitic Thyristor Equivalent Circuit



Terminal Breakdown

Soft error

- Non-destructive change in CMOS based storage devices
- Ionization impacts a single/multiple cell/register/FF, causing change of state
- The change is
  - Random
  - Non recurring.
  - Single and multi-bit
- Sources of the damage are
  - Alpha particles
  - Neutrons
  - Radiations.



Becoming more sever with scaling, since sources do not scale

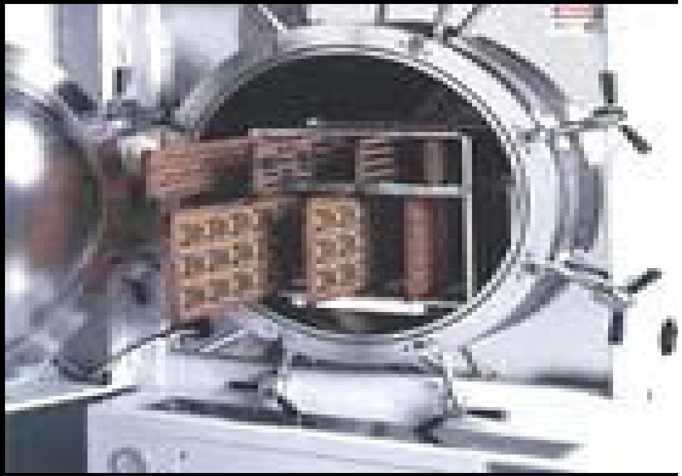
Reliability testing

- Reliability testing
  - In-house reliability testing
  - In-field reliability testing

- In-house reliability testing
  - A series of laboratory tests carried out under known stress conditions to evaluate the life span of a device
- Well known reliability tests
  - Burn-in
    - Early life burn in
    - High Temperature Operational Life (HTOL)
  - Highly Accelerated Stress Test (HAST)
  - Temperature cycle

In-house reliability testing……………. Burn in

- Early life burn-in eliminates units with marginal defects
- Conditions
  - Temperature 125^{o}C
  - Time= 48-168 hours

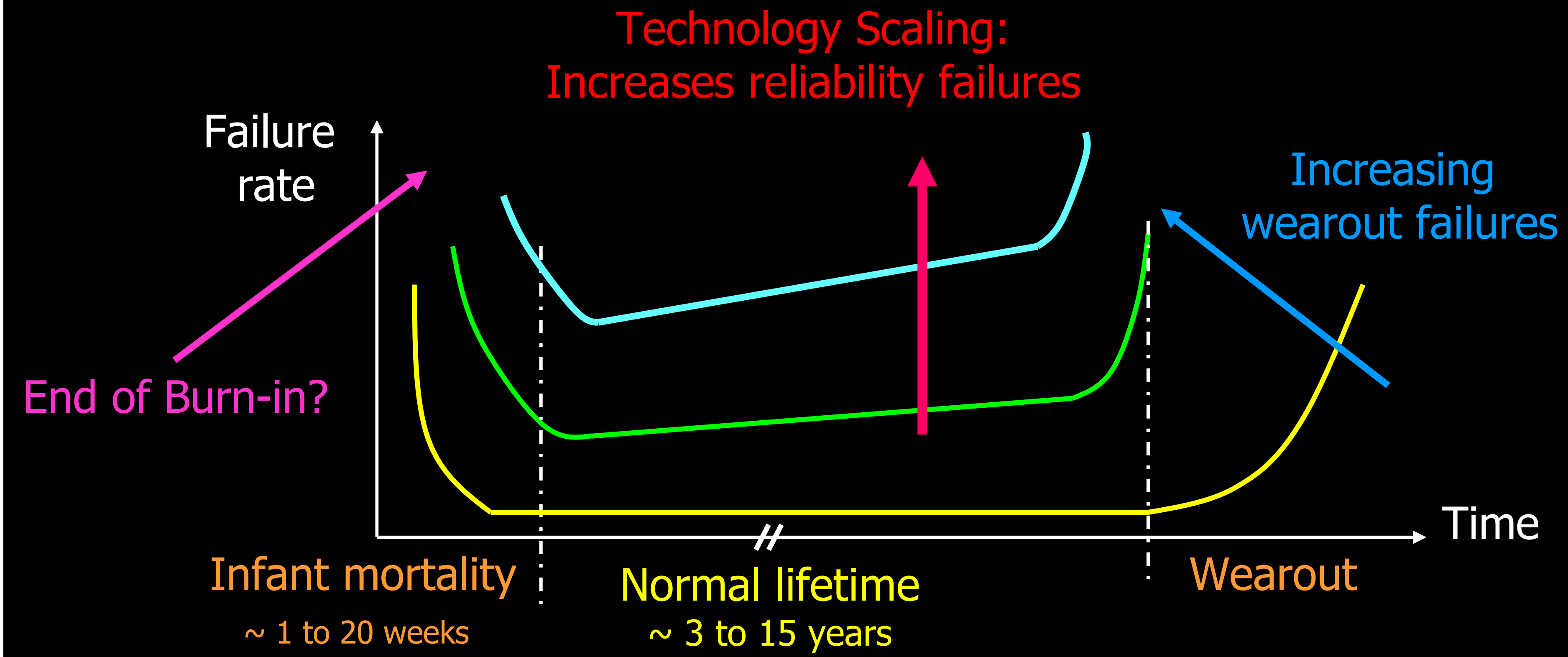


- High Temperature Operational Life (HTOL)
- HTOL determine high temperature lifetime of device under test
- Conditions
  - Temperature 125^{o}C
  - Time= 500-1000 hours

In-house reliability testing……. HAST, TCT

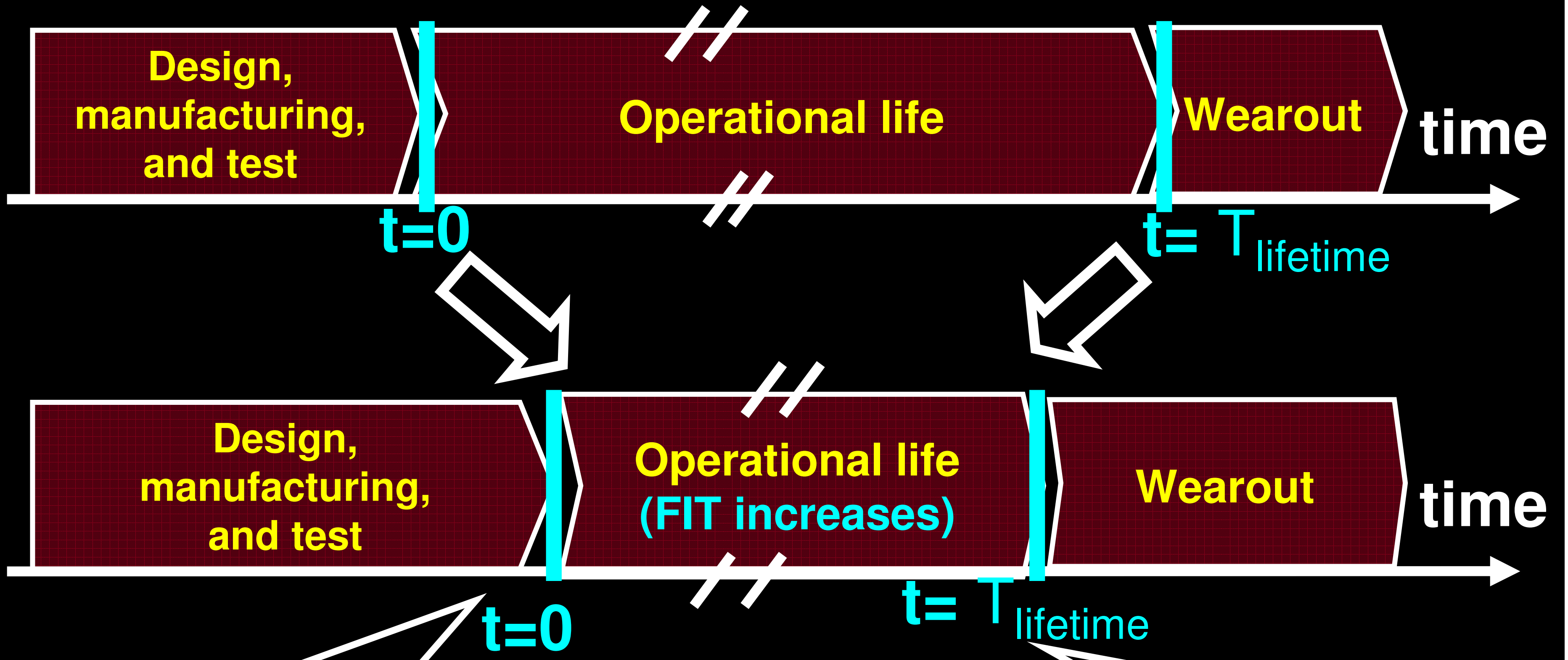
- Highly Accelerated Stress Test (HAST)
- Accelerate metal corrosion
- Conditions
  - Temperature 130^{o}C
  - Relative humidity 85%
  - Time 96-100 hours
- Temperature cycle test
- To test for resistance at very high and very low temperature
- To test for cyclic stresses
- Conditions
  - Minimum of 10 cycles
  - -55^{o}C to 85^{o}C
  - -55^{o}C to 125^{o}C

Reliability testing …………. Concerns



Shifting Bath tub curves limits benefits of in-house testing

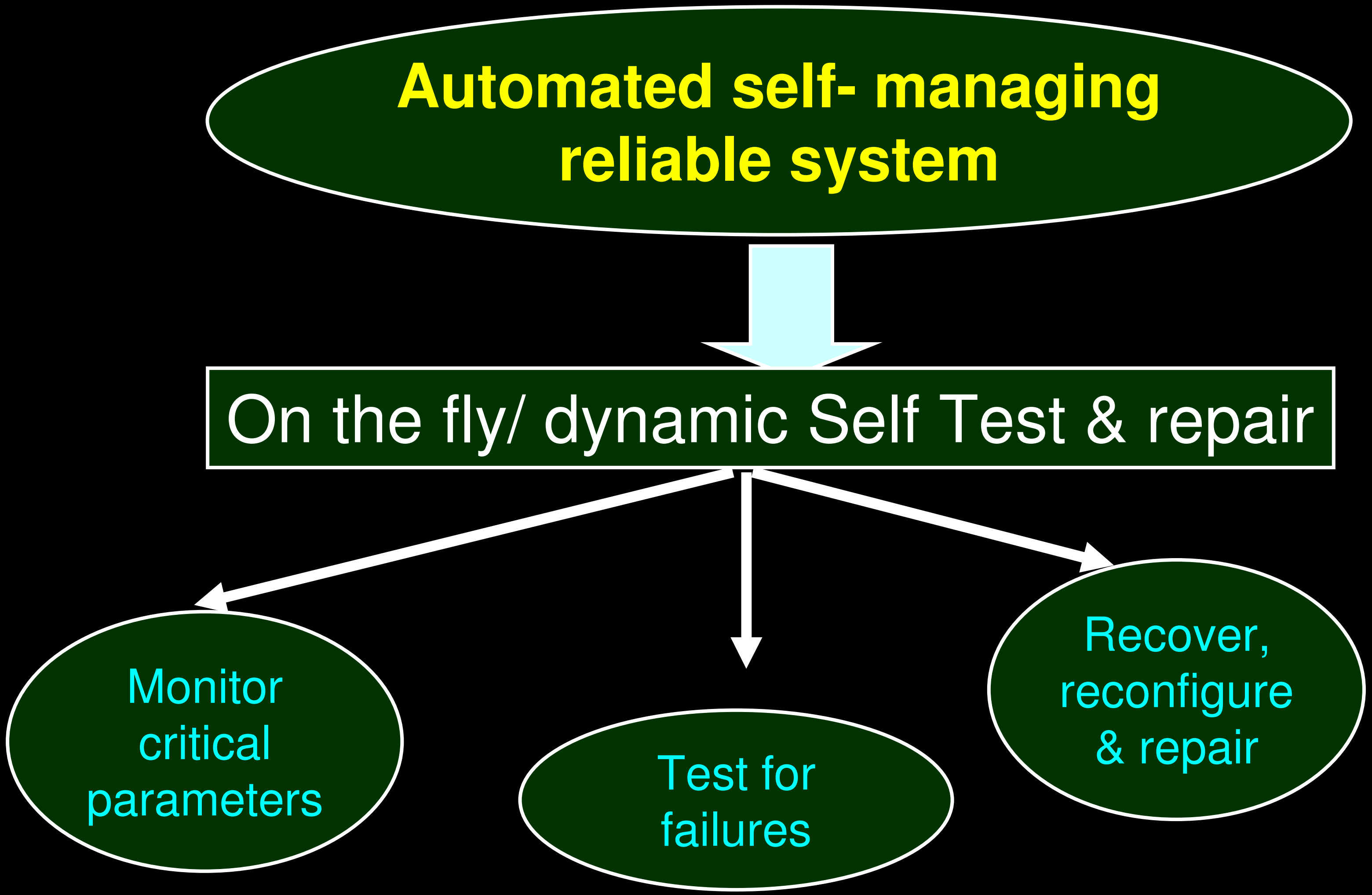
Reliability testing……………



- Design & verification
- Test & DFT
- DPM reduction
- ..

- Fault tolerance
- Defect tolerance
- Repair
- Reconfigurable ..
- ..

On Field Reliability testing and recoveery



Automated self- managing reliable system

On the fly/ dynamic Self Test & repair

Monitor critical parameters

Test for failures

Recover, reconfigure & repair

Future reliability challenges

- Ideal scaling law
  - 30% decrease in oxide thickness
  - 30% decrease in supply voltage
- Voltage cannot follow the scaling law
- The non-ideal scaling will accelerate reliability failures

- Smaller feature size
  - Narrow operation margin
  - Leakage current
  - Direct tunneling

- Thermal dissipation
  - Higher power density accelerate device failures
- New materials and processes
  - High-K dielectric
  - Carbon Nano Tubes (CNT)
  - 50 new processes per generation
- Device complexity

Conclusion

- Reliability is of main concern due to
  - People lives
  - Business survival
  - Larger profit margin
- Semiconductor reliability is more critical due
  - High complexity
  - Based on material physics
- Current reliability threats spans over
  - Transistors
  - Interconnects
  - Environment
- Reliability testing
  - In house testing
  - On field testing
- Reliability future is very challenging
  - High electric field
  - High complexity
  - New materials and processes