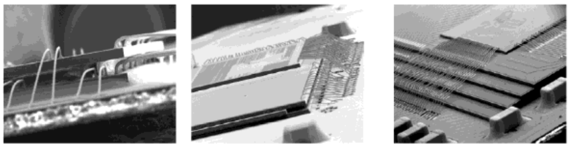
Micro and Nano- Electronics Reliability
Classical approach and new trends

Part 3: Qualification – Accelerated tests – Failure Analysis



Qualification

Includes all activities which ensures that the nominal design
and the manufacturing will meet or exceed the reliability targets

---

Qualification

- Qualification: All activities ensuring that design and manufacturing will achieve the required level of reliability
  - ➢ Purpose: Define acceptable levels of variability for all the critical parameters of a product.
- Tools:
  - ➢ In design phase: numerical simulations and analytical
  - ➢ Under development: prototyping
  - ➢ In production: pilot batches
- Knowledge required:
  - ➢ degradation mechanisms
  - ➢ acceleration factors
  - ➢ constraints (mission profiles)

Life stages

Design
Manufacturing and rework
Test
Screening""
Storage
Handling
Transportation
Operational life
Repair

Stressors

- T
- ∆T
- Vibrations
- Moisture
- *Radiations*
- I, V
- *EMC*
- Chemical
- Dusts
- Pressure

Accelerated testing

Accelerated testing

- The purpose of accelerated life testing is to induce field failure in the laboratory at a much faster rate by providing a harsher, but nonetheless representative, environment. In such a test the product is expected to fail in the lab just as it would have failed in the field, but in much less time.
- The main objective of an accelerated test is either of the following:
  - ➢ To discover failure mechanisms
  - ➢ To predict the normal field life from the high stress lab life

Methods of acceleration

- Increase the use rate of the product
  - ➢ appropriate for products that are ordinarily not in continuous use
- Increase the intensity of the exposure to radiation
  - ➢ Modeling and acceleration of degradation processes by increasing radiation intensity is commonly done in a manner that is similar to acceleration by increasing use rate.
- Increase the aging rate of the product
  - ➢ Temperature: main accelerator
  - ➢ Humidity
- Increase the level of stress (e.g., amplitude in temperature cycling, voltage, or pressure) under which test units operate.

- Combinations of these methods

Accelerated testing

- An Accelerated testing program can be broken down into the following steps:
  - ➢ Define objective and scope of the test
  - ➢ Collect required information about the product
  - ➢ Identify the stress(es)
  - ➢ Determine level of stress(es)
  - ➢ Conduct the Accelerated test and analyse the accelerated data

General failure mechanisms

Stressors

- T
- ∆T
- Vibrations
- Moisture
- Radiations
- I, V
- EMC
- Chemical
- Dusts
- Pressure

Mechanisms

- Inter-diffusion
- Oxidation
- Chemical reactions
- Corrosion
- Mechanical fatigue
- Crack
- Delamination
- Abrasion
- EOS
- Crystal degradation
- Charge trapping

Define the relationships

Known relationships

Mechanism	Design Item	Main Acceleration Factor
TDDB	Structure, Insulation film characteristics	Electric field Temperature
HCI	Transistor structure, Distribution of impurities	Electric field
NBTI	Transistor structure, Oxide film characteristics	Electric field Temperature
Electromigration	Wiring material, Structure, Current density	Current density Temperature
Stress-migration	Wiring material, Structure	Temperature Stress (CTE)
IMD-TDDB	Structure, Insulation film characteristics	Electric field Temperature

Aging tools

- Temperature storage
- Temperature cycling
- Thermal shocks
- Salt spray test chamber

- Temperature and humidity test chamber
- Combined vibration and temperature cycles test chamber

Aging tools in service

- https://www.youtube.com/watch?v=Nm0uPVQI12w

Different aging systems

- https://www.youtube.com/watch?v=rbmTdiUoxJ8

Thermal shocks

- https://www.youtube.com/watch?v=_pCL1LO5hPU

Vibration

- https://www.youtube.com/watch?v=ezQOFLk0qHc

Drop tests

Acceleration factor

$$AF = \frac{Time - to - fail(stress1)}{Time - to - fail(stress2)}$$

- Examples
    - Arrhenius Model
    - Eyring Model for Voltage Acceleration
    - Inverse Power Law Model
    - Peck's Law for Temperature Humidity

Acceleration factor

$$AF = \frac{Time - to - fail(stress1)}{Time - to - fail(stress2)}$$

- For a given failure mechanism, the ratio of the time it takes for a certain fraction of the population to fail, following application of one stress or use condition, to the corresponding time at a more severe stress or use condition.
- NOTE 1: Times are generally derived from modelled time-to-failure distributions (lognormal, Weibull, exponential, etc.).
- NOTE 2: Acceleration factors can be calculated for temperature, electrical, mechanical, environmental, or other stresses that can affect the reliability of a device.

From JEDEC Publication N° 122G

Statistical models for acceleration

- Physical acceleration models
    - For well understood failure mechanisms
    - In fact, very rare because extremely complicated
- Empirical acceleration models
    - Needs extensive empirical experiences
- Semi-empirical models

Temperature acceleration: Arrhenius model

- Most of the defect-related failures and wear-out mechanisms can be accelerated by using temperatures higher than the normal application temperature to induce the failure.
- The induced failure usually involves some kind of chemical or physical reaction.

Reaction rate $\propto$ exp (-Ea /kT)

Time to failure TTF $\propto$ 1/Reaction rate

TTF = A exp (Ea /kT) $AF_T = \exp[\frac{E_a}{k}(\frac{1}{T_1} - \frac{1}{T_2})]$

- Ea is the activation energy
- k is the Boltzmann's constant k = 1.38 x 10^{-23} JK^{-1} = 8.617 x 10^{-5} eVK^{-1}
- T_1 and T_2 are temperatures in Kelvin

Arrhenius Law of Temperature
Activation energy

- **Activation energy (*E*a):** The excess free energy over the ground state that must be acquired by an atomic or molecular system in order that a particular process can occur.
- Remark: The activation energy is used in the Arrhenius equation for the thermal acceleration of physical reactions. The term "activation energy" is not applicable when describing thermal acceleration of time-to-failure distributions, e.g., in the Arrhenius equation for reliability;
- → "Apparent activation energy"

Numerical example

- Assuming an activation energy of 0.7 eV, an accelerated test is performed at 150°C during 1000 hours without failure.
- What will be the minimum expected life time at 55°C?

TTF = A exp (Ea /kT) $AF_T = \exp[\frac{E_a}{k}(\frac{1}{T_1} - \frac{1}{T_2})]$

- Ea is the activation energy
- k is the Boltzmann's constant k = 1.38 x 10^{-23} JK^{-1} = 8.617 x 10^{-5} eVK^{-1}
- T_1 and T_2 are temperatures in Kelvin

Numerical example

- Assuming an activation energy of 0.7 eV, an accelerated test is performed at 150°C during 1000 hours without failure.
- What will be the minimum expected life time at 55°C?

$$AF_T = \exp[\frac{E_a}{k}(\frac{1}{T_1} - \frac{1}{T_2})]$$

AF = 260
Total equivalent operating time = test time x AF = 1000 hr x 260 = 29.6 years

Some orders of magnitude for Ea

Mechanism	Temperature Ea (eV)
Gate-oxide defect	0.3
Intermetallic defect	0.3
Poly to metal defect	0.3
Silicon junction defect	0.8
Masking defect	0.5
Electromigration	0.5
Contamination	1.0
Assembly	0.5
Hot carrier	-1.0
Intermetallic growth	1.0
Corrosion	0.3 to 1.1

Remarks

- The values are « typical » ones, but depend on technology: must be taken with care
- All the Ea are positive except the hot carrier, Ea= -1 eV.
  - At a lower temperature, the hot carrier has less scattering from lattice vibration; therefore, the degradation is faster.
  - So, for the hot carrier, low temperature needs to be used for the accelerated test.

    - At a lower temperature, the hot carrier has less scattering from lattice vibration; therefore, the degradation is faster.

EXERCISE *(from Jedec Standard 91A)* *1/2*

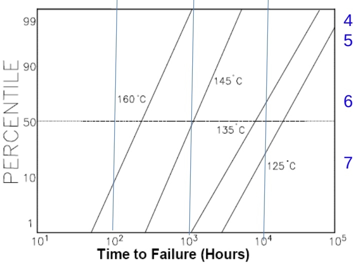
- A wire bond product was fabricated with aluminum wire ultrasonically bonded to a copper pad. With use, it exhibited a wear-out problem due to bond lifting in the presence of variable surface oxides. An experiment was performed to develop the acceleration effect of bake time with wire bond resistance, as contact points decreased with corrosion of the Al/Cu bond sites.
- Samples were randomly selected from several production lots and evenly distributed over 4 temperature cells ranging from 125°C to 160°C. All cells were stressed beyond the 50% fail point (t_{50}), with a minimum of 5 readouts in each cell. A failure was defined as a change in wire bond resistance greater than 15 milliohms from its original value.

1. What is here the failure MODE?
2. What is the failure MECHANISM?
3. What is the failure CRITERION?

EXERCISE *(from Jedec Standard 91A)* *2/2*

Accelerated test results

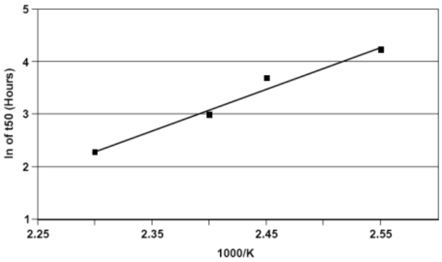
- Results of the experiment are summarized below, a lognormal plot of cumulative percent failures versus stress time. The failure distributions of Al/Cu wire thermal degradation are well behaved and have similar shape parameters, indicating that the degradation mechanism is consistent throughout the product chips.



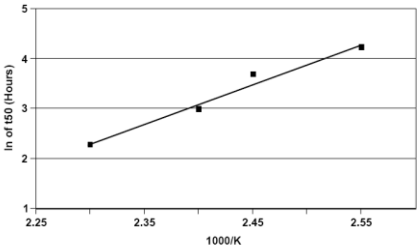
4. Comment the last sentence
5. Plot ln(t_{50}) as a function of 1000/T where T is the temperature expressed in K
6. Derive from that curve that the failure follows an Arrhenius law
7. Calculate the activation energy Ea

Solutions (1/2)

1. Failure MODE : Increase in resistance
2. Failure MECHANISM : Ball bond lift due to corrosion
3. Failure CRITERION: 15mΩ increase in resistance
4. Slope similar: Failure mechanisms are supposed to be similar
5.



Solutions (2/2)



- $\mathrm{Log}(t_{50}) = a(A(1000/T)+b$
  hence $t_{50} = A \exp aT$ similar to $TTF = A \exp (\frac{E_a}{kT})$
- The activation energy Ea is 2eV

General Eyring’s model

- Sometimes the reaction rate of a process relies on more than one stress
  - ➢ Humidity
  - ➢ Voltage
- Eyring's contributions to chemical reaction rate theory have led to a very general and powerful model for acceleration known as the Eyring Model.

$$t_f = AT^{\alpha}\exp\left[\frac{\Delta H}{kT} + \left(B + \frac{C}{T}\right)\cdot S_1 + \left(D + \frac{E}{T}\right)\cdot S_2\right]$$

- S_1 S_2 : stressors ΔH : Activation energy (Ea)
- α, A, B, C, D, E : parameters to be determined

General Eyring’s model

- The general Eyring model includes terms that have stress and temperature interactions
  - ➢ The effect of changing temperature varies, depending on the levels of other stresses
- Most models in actual use do not include any interaction terms
  - ➢ The relative change in acceleration factors when only one stress changes does not depend on the level of the other stresses.
  - ➢ In models with no interaction, you can compute acceleration factors for each stress and multiply them together.
  - ➢ To first approximations, it seems to work for many cases

Simplified Eyring’s model

- Theoretical basis from chemistry and quantum mechanics.
- Includes temperature and can be expanded to include other relevant stresses.
- Assumes that the contribution of each stress on the reaction rate is independent
- The temperature term by itself is very similar to the Arrhenius empirical model, explaining why that model has been so successful in establishing the connection between the Ea parameter and the quantum theory concept of "activation energy needed to cross an energy barrier and initiate a reaction"

Acceleration models…

- Many well-known models are simplified versions of the Eyring model with appropriate functions of relevant stresses chosen for S_1 and S_2.
- The trick is to find the right simplification to use for a particular failure mechanism.
- Standardized models are available
  - ➢ All using exponential and/or power functions
  - ➢ TTF = $A\,(S_1)^n \exp \alpha\, S_2$
    - α and n either positive or negative

Eyring’s model: Voltage acceleration

- Voltage-stress failure mechanism depends on device structure and type : different models
- Example: MOS devices gate-oxide resistance to voltage stress
  - ➢ Eyring-exponential model works well: lifetime t can be expressed as a function of stress voltage V_S

$$TTF = t = A \exp\{-\beta V_S\}$$

A constant depending on device structure (s)

β voltage acceleration coefficient for a given failure mechanism (V^{-1})

$$AF = \exp\{-\beta(V_s - V_o)\}$$

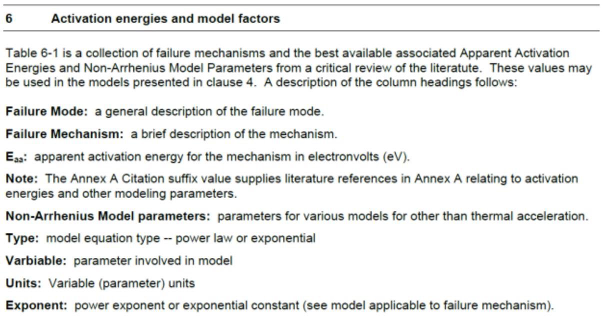
Lifetime t_S obtained from V_s,
Operating lifetime t_O, corresponding to operating voltage V_o

Eyring's model: Voltage acceleration numerical examples

Mechanism	β (1/v)
Thin-gate-oxide defect	Tox/100
Intermetallic defect	1.5 to 3.0
Poly to metal defect	1.5 to 3.0
Silicon junction defect	0.0 to 0.5

AOS_reliability-handbook

Extract from JEDEC standard 122G



6 Activation energies and model factors

Table 6-1 is a collection of failure mechanisms and the best available associated Apparent Activation Energies and Non-Arrhenius Model Parameters from a critical review of the literatute. These values may be used in the models presented in clause 4. A description of the column headings follows:

Failure Mode: a general description of the failure mode.

Failure Mechanism: a brief description of the mechanism.

E_{aa}: apparent activation energy for the mechanism in electronvolts (eV).

Note: The Annex A Citation suffix value supplies literature references in Annex A relating to activation energies and other modeling parameters.

Non-Arrhenius Model parameters: parameters for various models for other than thermal acceleration.

Type: model equation type -- power law or exponential

Varbiable: parameter involved in model

Units: Variable (parameter) units

Exponent: power exponent or exponential constant (see model applicable to failure mechanism).

Extract from JEDEC standard 122G

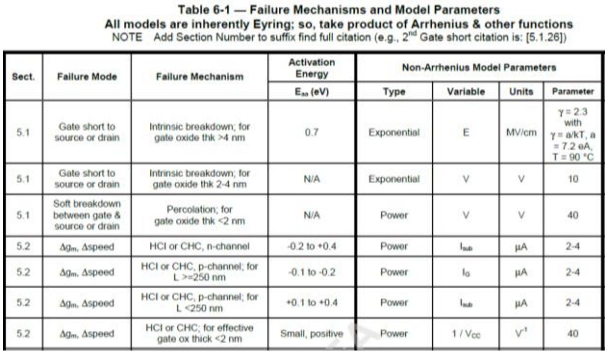


Table 6-1 — Failure Mechanisms and Model Parameters

All models are inherently Eyring; so, take product of Arrhenius & other functions

NOTE Add Section Number to suffix find full citation (e.g., 2nd Gate short citation is: [5.1.26])

Sect.	Failure Mode	Failure Mechanism	Activation Energy	Non-Arrhenius Model Parameters			
			E_{aa} (eV)	Type	Variable	Units	Parameter
5.1	Gate short to source or drain	Intrinsic breakdown; for gate oxide thk >4 nm	0.7	Exponential	E	MV/cm	$\gamma = 2.3$ with $\gamma = a/kT$, $a = 7.2$ eA, $T = 90$ °C
5.1	Gate short to source or drain	Intrinsic breakdown; for gate oxide thk 2-4 nm	N/A	Exponential	V	V	10
5.1	Soft breakdown between gate & source or drain	Percolation; for gate oxide thk <2 nm	N/A	Power	V	V	40
5.2	Δg_m, Δspeed	HCI or CHC, n-channel	-0.2 to +0.4	Power	I_{sub}	µA	2-4
5.2	Δg_m, Δspeed	HCI or CHC, p-channel; for L >=250 nm	-0.1 to -0.2	Power	I_G	µA	2-4
5.2	Δg_m, Δspeed	HCI or CHC, p-channel; for L <250 nm	+0.1 to +0.4	Power	I_{sub}	µA	2-4
5.2	Δg_m, Δspeed	HCI or CHC; for effective gate ox thick <2 nm	Small, positive	Power	$1 / V_{CC}$	V^{-1}	40

Eyring's model example
Peck's Law for Temperature and Humidity

TTF = A M^{-n} exp (Ea /kT)

A constant depending on material, process, condition (unit: s $\%RH^{n}$)

M moisture level (%RH)

M_{use} in service

M_{test} in test

n material constant (no unit)

$$AF = \left(\frac{M_{use}}{M_{test}}\right)^{-n} \exp\left[\frac{E_a}{k}\left(\frac{1}{T_{use}} - \frac{1}{T_{test}}\right)\right]$$

Eyring's model example
Black's Law for Electromigration

TTF = A J^{-n} exp (Ea /kT)

A constant depending on geometry (unit: s Am^{-2n})

J current density (Am^{-2})

J_{use} in service

J_{test} in test

n parameter related to current density accounting for current flow effects other than Joule heating (no unit)

$$AF = \left(\frac{J_{use}}{J_{test}}\right)^{-n} \exp\left[\frac{E_a}{k}\left(\frac{1}{T_{use}} - \frac{1}{T_{test}}\right)\right]$$

Defining accelerated test conditions

- For a known or suspected failure mechanism,
  - ➢ Identify all stimuli affecting the mechanism based on anticipated application conditions and material capabilities:
    - ✓ temperature
    - ✓ electric field
    - ✓ humidity,
    - ✓ thermomechanical stresses,
    - ✓ vibration,
    - ✓ corrosive environments.

Defining accelerated test conditions

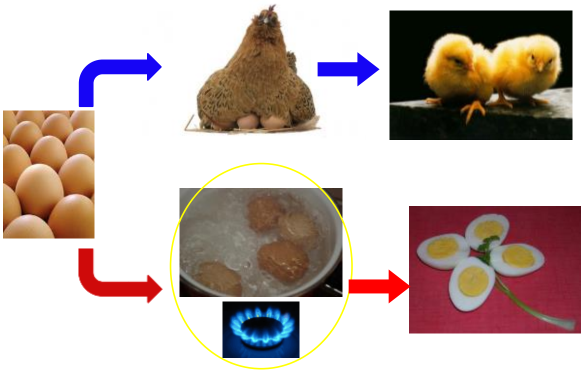
- Choice of accelerated test conditions based on
  - material properties
  - application requirements (“mission profile”).

- Need to conduct accelerated tests over a reasonable time interval.

BUT avoid

  - generating fails that are not pertinent to the experiment,
    - ✓ due to stress equipment problems
    - ✓ due to materials problems,
    - ✓ “false failures” caused by product overstress conditions that will never occur during actual product use

Bad accelerating conditions



Some bibliographic references

- AOS reliability-handbook
- Jedec standards JEP122
- https://accendoreliability.com/eyring-model/

Failure analysis

Why is failure analysis necessary?

- Failure analysis is an investigation of failure mode and mechanism using
  - electrical,
  - physical,
  - chemical

analysis techniques

- Failure analysis of semiconductor devices is necessary
  - to clarify the cause of failure
  - to provides rapid feedback of this information to the design and manufacturing process stages.

Failure analysis procedure

- Visual inspection of the package.
- Electrical characteristics are checked to analyze the failure mode.
- Non destructive physical observation
- Then package is opened and the chip is analyzed according the failure mode.
  - Optical microscopes
  - scanning electron microscopes (SEMs) are used to observe the failed point (physical analysis).
- Finally failure mechanism is determined
- Corrective actions provided.

Failure analysis - main steps

- Gathering Information
- Electrical Testing
  - ➢ Knowledge required
    - Circuit Operation
    - Digital Circuit Troubleshooting
    - Analogue Circuit Troubleshooting
  - ➢ Main tools
    - Curve Tracer/Parameter Analyzer
    - Quiescent Power Supply Current
    - Parametric Tests (Input Leakage, Output voltage levels, Output current levels, etc.)
    - Timing Tests (Propagation Delay, Rise/Fall Times, etc.)
    - Automatic Test Equipment

https://semitracks.com/courses/analysis/failure-and-yield-analysis.php

Tools: Electrical testers

Failure analysis - main steps, main tools

- Package Level Testing
  - ➢ Optical Microscopy
  - ➢ Acoustic Microscopy
  - ➢ X-Ray Radiography
  - ➢ Hermetic Seal Testing
  - ➢ Residual Gas Analysis

Acoustic Microscope

X-ray Radiography

http://www.cascade-eng.com/reliability_docLibrary.html

Failure analysis - main steps, main tools

- Decapsulation/Backside Sample Preparation
  - ➢ Mechanical Delidding Techniques
  - ➢ Chemical Delidding Techniques
  - ➢ Backside Sample Preparation Techniques
- Die Inspection
  - ➢ Optical Microscopy
  - ➢ Scanning Electron Microscopy
- Microprobing
  - ➢ Standard
  - ➢ AFM Probing
  - ➢ Nanoprobing
- Photon Emission Microscopy

https://semitracks.com/courses/analysis/failure-and-yield-analysis.php

Tools: Scanning electron microscopes

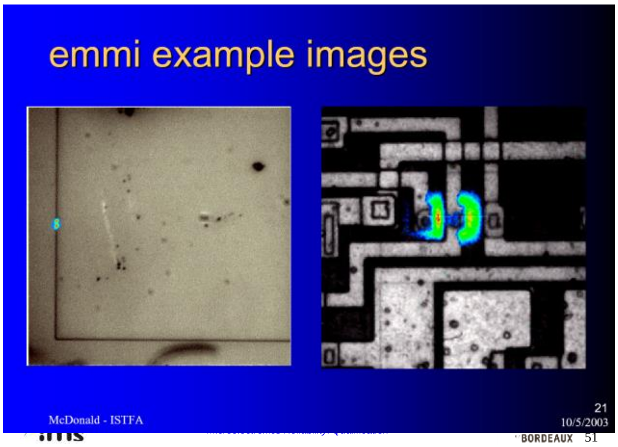
Failure analysis - main steps, main tools

- Electron Beam Tools
  - ➢ Voltage Contrast
    - Passive Voltage Contrast
    - Static Voltage Contrast
    - Capacitive Coupled Voltage Contrast
  - ➢ Electron Beam Induced Current
  - ➢ Resistive Contrast Imaging
  - ➢ Charge-Induced Voltage Alteration

Failure analysis - main steps, main tools

- Optical Beam Tools
  - Optical Beam Induced Current
  - Light-Induced Voltage Alteration
  - Thermally-Induced Voltage Alteration
  - Seebeck Effect Imaging
  - Electro-optical Probing
  - Laser Voltage Probe (IDS-2K)
- Thermal Detection Techniques
  - Infrared Thermal Imaging
  - Liquid Crystal Hot Spot Detection
  - Fluorescent Microthermal Imaging

Examples of Light Emission Microscopes

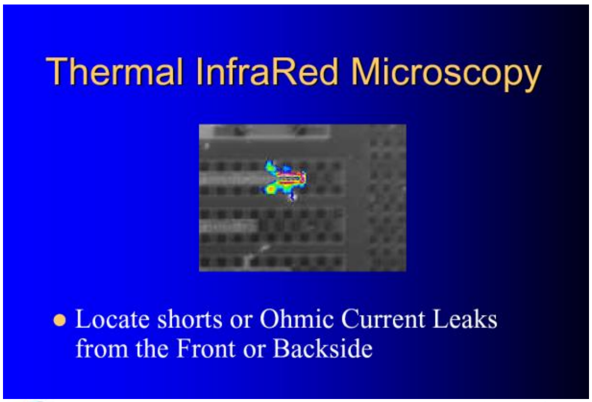


emmi example images

McDonald - ISTFA

21

10/5/2003



Thermal InfraRed Microscopy

- Locate shorts or Ohmic Current Leaks from the Front or Backside

Failure analysis - main steps, main tools

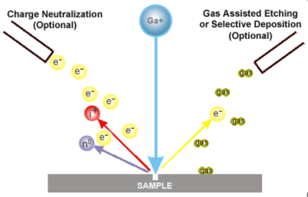
- Chemical Unlayering
  - Wet Chemical Etching
  - Reactive Ion Etching
  - Parallel Polishing
- Scanned Probe Techniques
  - Atomic Force Microscopy
  - Scanning Capacitance Microscopy
  - SQUID Microscopy

Failure analysis - main steps, main tools

- Analytical Techniques
  - TEM
  - EDS/WDS
  - ESCA/XPS
  - Auger
  - SIMS
  - Focused Ion Beam

http://www.cascade-eng.com/reliability_docLibrary.html

Focused Ion Beam Systems



Impossible d'afficher l'image.

Summary an example of failure analysis procedure