Electronics Failure Analysis: Mechanisms, Techniques, & Simple Debug Tools

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Instructor Biography

- Cheryl Tulkoff has over 22 years of experience in electronics manufacturing with an emphasis on failure analysis and reliability. She has worked throughout the electronics manufacturing life cycle beginning with semiconductor fabrication processes, into printed circuit board fabrication and assembly, through functional and reliability testing, and culminating in the analysis and evaluation of field returns. She has also managed no clean and RoHS-compliant conversion programs and has developed and managed comprehensive reliability programs.

- Cheryl earned her Bachelor of Mechanical Engineering degree from Georgia Tech. She is a published author, experienced public speaker and trainer and a Senior member of both ASQ and IEEE. She holds leadership positions in the IEEE Central Texas Chapter, IEEE WIE (Women In Engineering), and IEEE ASTR (Accelerated Stress Testing and Reliability) sections. She chaired the annual IEEE ASTR workshop for four years and is also an ASQ Certified Reliability Engineer.

- She has a strong passion for pre-college STEM (Science, Technology, Engineering, and Math) outreach and volunteers with several organizations that specialize in encouraging pre-college students to pursue careers in these fields.
Effective failure analysis is critical to product reliability. Without identifying the root causes of failure, true corrective action cannot be implemented and the risk of repeat occurrence increases. A systematic approach to failure analysis is recommended - proceeding from non-destructive to destructive methods until all root causes are conclusively identified. Choosing the appropriate techniques based upon the failure information (failure history, failure mode, failure site, failure mechanism) specific to your product is also critical. Learn how in this webinar!

- **Introduction**

- **Most Common Failure Mechanisms**
  - On-die mechanisms (ESD, electro-migration, TDDB, passivation & dielectric cracking)
  - 1st level packaging (wirebonds, solder bumps, substrates, leadframes)
  - Support structures (die attach, underfill, encapsulant)
  - Solder joints (thermal fatigue, IMC growth, solderability)
  - Board level (passives, PCB, CAF, PTH, tin whiskers, finishes)

- **Failure Analysis Techniques**
  - Failure analysis sequence
  - NDE techniques (visual, optical, electrical, thermal, acoustic, X-ray, SQUID)
  - Destructive techniques (decapsulation, etching, cross-sectioning, SEM, EDX, XRF, Auger, SIMS, FIB, electrical and optical beam techniques)
  - Others (FTIR, DSC, TMA, ionic chromatography)

- **Simple Debug Tools to Consider**
General Words of Wisdom on FA

- Before spending time and money on Failure Analysis, consider the following:
  - Consider FA “order” carefully. Some actions you take will limit or eliminate the ability to perform follow on tests.
  - Understand the limitations and output of the tests you select.
  - Use partner labs who can help you select and interpret tests for capabilities you don’t have. Be careful of requesting a specific test. Describe the problem and define the data and output you need first.
  - Pursue multiple courses of action. There is rarely one test or one root cause that will solve your problem.
  - Don’t put other activities on hold while waiting for FA results. Understand how long it will take to get results.
  - Consider how you will use the data. How will it help you?
    - Information?
    - Change course, process, supplier?
    - Don’t pursue FA data if it won’t help you or you have no control over the path it might take you down. Some FA is just not worth doing
Commonly Used Lab Test, Analysis & Reference Standards

- **IPC-TM-650: Test Methods Manual**
  - Series available for free download at [www.ipc.org](http://www.ipc.org)
    - Section 1.0: Reporting and Measurement Analysis Methods
    - Section 2.1: Visual Test Methods
    - Section 2.2: Dimensional Test Methods
    - Section 2.3: Chemical Test Methods
    - Section 2.4: Mechanical Test Methods
    - Section 2.5: Electrical Test Methods
    - Section 2.6: Environmental Test Methods
Why is this Knowledge important?

- There are always more problems than resources!
- If you don’t analyze, learn from, and prevent problems, you simply repeat them. Your list never gets smaller.
- Let’s review some simple examples before we get started.
Example Issues: Design & Process Related

These 2 images show issues with the wave pallet and wave solder process. Excess flux residue and solder stringing are present. These result in immediate and longer term issues.

This image shows the same flux and solder issues and also shows a staking compound used under the cap. Make sure this compound is compatible with both the soldering materials and the operating environment.
Using the previous photos, what mechanisms should I be concerned with and what FA techniques might be appropriate?

- **Mechanisms**
  - Corrosion: Excess weak organic acids (WOAs)
  - Electrochemical-migration: WOAs plus solder stringers
  - Electrical Failure: shorts

- **Techniques**
  - Visual Inspection
  - Ion Chromatography
  - Surface Insulation Resistance Testing

- What else?
Example Issue Continued

- What root cause fixes might be pursued?
  - Change layout or parts selection to avoid selective wave soldering
  - Reduce flux volume / improve flux application control
  - Clean wave pallets routinely
  - Improve wave pallet design

- What “band-aids” might be pursued?
  - Cleaning
  - Inspection
  - Tests
Example Issues: Parts Selection & Use

These images show some very common cable / connector issues. Interconnect failures are one of the major causes of system failure!
Using the previous photos, what mechanisms should I be concerned with and what FA techniques might be appropriate?

- **Mechanisms**
  - Wearout: strain relief, temperature, insertion
  - Electrical Failure: shorts or opens

- **Techniques**
  - Visual Inspection
  - Materials characterization
  - Thermal and mechanical cycling

- What else?
Example Issues Continued

- What root cause fixes might be pursued?
  - Evaluate alternate means of interconnect
  - Appropriate strain relief
  - Having cable selection and use criteria in place
  - Appropriate parts selection
    - Is cable rated/meant for your use environment
      - Temperature, time, chemical exposure, insertion cycle #, length, insulation, conductor size

- What “band-aids” might be pursued?
  - Inspection
  - Spare cables, forced replacement or changeout
  - Tests
Common Failure Mechanisms
IC Components: Most Common Failures

- Broken wires and lifted bonds: 32.2%
  - Most often stitch bonds
- Die cracking and/or damage: 15.5%
  - Chipping, passivation cracking, or metal traces breaking
- Interface delamination: 12.7%
  - Mold/die interfaces
- Wafer defects: 12.2%
  - Surface damage or scratches (handling)
- Package cracking: 10.2%
  - Substrates and package
- Others: 17.2%
  - Solderability, foreign materials/contamination

*Intrinsic device structure rarely implicated!*

Source: Yang, Bernstein, Gajewski, & Walls, 40th IMAPS Conf., San Jose 2007
Components: Failure Mechanisms

- **On-Die**
  - Process defects: extremely difficult to perform failure analysis on
    - Often screened by manufacturer and addressed during R&D and New Product Introduction (NPI)
  - ESD – Electrostatic Discharge
  - Electro-migration
  - Time-dependent dielectric breakdown (TDDB)
  - Passivation cracking
  - Dielectric cracking
  - On-die mechanisms are often extremely difficult to diagnose without significant assistance from the manufacturer
    - Manufacturer’s response depends on strength of business relationship
Components: Failure Mechanisms

- 1\textsuperscript{st} Level Interconnects (electrical connections)
  - Wirebonds: contamination-induced failure; flexural fatigue (excessive length); substrate fracture due to excessive force; lifting; heel cracking; Kirkendall voiding
  - Solder bumps: poor wetting/adhesion; fracture; thermo-mechanical fatigue; intermetallic growth
  - Substrates: bulk cracking; opens in copper lines; via interface contamination; line-to-via cracking; contaminants; unfilled vias
  - Leadframes: cracking (rare), stamping/etching defects; bridging metal fibers
Components: Failure Mechanisms

- **Support Structures**
  - Die attach: delamination; contamination; material selection; insufficient curing
  - Underfill: delamination; contamination; poor viscosity/flow; material selection; insufficient curing
  - Encapsulant: delamination; wirebond contact due to high viscosity; material selection (moisture, flame retardants); insufficient curing; trapped moisture/“popcorning”

- **2nd Level Interconnects**
  - Solder joints: thermo-mechanical fatigue; intermetallic (IMC) growth and fracture; solderability

- **Board Level**
  - Passives failure mechanisms: ceramic, electrolytic, & Aluminum/Tantalum (Al/Ta) capacitors; resistors
  - PCB: pad cratering; buckling; conductive anodic filaments (CAF); delamination; trace peeling
  - Plated through-hole (PTH): fracture; thermo-mechanical fatigue; voids/etch pits
  - Surfaces: electro-chemical migration (ECM); tin whisker growth; “black pad” on Electroless Nickel Immersion Gold (ENIG) finishes
Component: Failure Mechanisms - ESD

Electrostatic Discharge (ESD)

- Objects moving with respect to each other transfer charge
  - Amount depends on materials, speed, proximity
  - Dissipation depends on conduction paths
- Extremely large voltages possible
  - Dry environment
  - Materials with easily stripped electrons
  - No discharge path
- Human perception > 5 kV
  - Circuits long since destroyed
Component Failure Mechanisms: ESD

- Two primary failure mechanisms:
  - Electric field-induced
    - Silicon dioxide breakdown ~ $7 \times 10^8$ V/m
      - 60Å oxide destroyed at ~ 4.2V
      - Shorts gate permanently
    - Fields could push carriers into insulators
      - May just degrade performance
  - Thermal destruction
    - Any resistance in path subject to local intense heating
      - Contacts, vias, and junctions
      - Weakest link goes first
    - May also produce “walking wounded” / latent damage
      - Increased leakage
      - Increased resistance
      - Softened junctions
- All protection techniques fail eventually
  - Class A, B, & C specifications are 1kV, 2kV, & 4kV, respectively
ESD Failure Modes

- Different ESD models tend to produce different types of failure and require different types of control and protection.

- Basic failure mechanisms include
  - Oxide punchthrough
  - Junction burnout
  - Metallization burnout

Drain-junction damage in an NMOS after HBM stress. Note the thermal damage to silicon. Image courtesy of TI

Gate-oxide damage to an input buffer after CDM stress. Note the rupture in gate oxide. Image courtesy of TI
Often difficult to distinguish between EOS/EOL (electrical overstress and electrical overload) and ESD. Some rules of thumb:

- **ESD damage**
  - Small failure sites
  - Not always visible without deprocessing
  - No visible evidence at the package level

- **EOS damage**
  - Large areas of damage
  - Burned silicon and metallization
  - Sometime visibly evident package damage
Trying to distinguish between EOS & ESD

- **EOS**: Thermal overstress to a component’s circuitry
  - Short Pulse Width Failure – Junction Spiking
  - Long Pulse Width Failures – Melted metallization and open bond wires
  - Junction spiking occurs when the amount of Al migration into the silicon substrate has reached the point wherein the Al has penetrated deep enough so as to short a p-n junction in its path. By that time an Al spike is said to have shorted the junction, damaging the device permanently.
Electro-migration (the Electron Wind)

- Affects interconnects
  - Collisions of electrons proportional to current density causes dislodged electrons

- Characterized by the migration of metal atoms in a conductor downstream of the electron flow.
  - Induces opens, voids or hillocks

- Accelerated by temperature, voltage, and frequency
  - Effectively accelerated by HTOL
Component Failure Mechanisms: Electro-Migration

- Metal atom diffusion fastest along grain boundaries
- Variation in lifetime of lines due to grain boundary orientation and geometric defects
Continuous application of stress to gate oxide eventually causes insulating film breakdown - TDDB

- Two categories:
  - Initial intermittent failure: sporadic breakdown due to gate oxide defects
  - Genuine breakdown: complete failure due to intrinsic performance of gate oxide

Source: Sony Products – Failure Mechanisms
Time Dependent Dielectric Breakdown

- Charges trapped in various parts of the oxide as current flows in the oxide
  - Creates high electric fields.
- Sum of electric fields exceeds dielectric breakdown in weakest points of dielectric.
  - Excess heat in the dielectric promotes increased current flow.
  - Positive feedback loop eventually results in electrical and thermal runaway.
- TDDB is accelerated by temperature and voltage
  - Primary function of high temp operating life (HTOL) testing
Component Failure Mechanisms: Passivation Cracking

- Acceleration model:

\[ t_f = \frac{C}{(RH)^b} \cdot \exp \left( \frac{E_a}{k_b T} \right) \]

- Cracking due to intrinsically weak interfaces between passivation layers and substrates
- Assisted by stress corrosion cracking in the presence of water vapor: rupture of Si-O bonds, crack formation, and surface termination with –OH groups
- Exacerbated by package-induced and environmental stresses

Source: Craigin, Texas Instruments, 2004

DDC118 5.0kV 4.9mm ×6.00k SE(U)

Source: Craigin, Texas Instruments, 2004
Component Failure Mechanisms: Dielectric Cracking

- **Primary failure modes:**
  - Micro-delamination from the substrate
  - Particulate/film contamination
  - Microvoids, micro-channels, and/or cracks

- **Sensitive to process conditions**
  - Substrate temperature
  - Gas mix
  - Flow rate

- **Accelerated by thermal stresses and moisture,** like passivation cracking
Component Failure Mechanisms: Wirebonds

- **Primary failure modes:**
  - Poor adhesion due to surface contamination
  - Failure during shock/vibration due to flexural fatigue
  - Substrate fracture due to excessive force

- **Secondary failure modes:**
  - Lifting
  - Heel cracking
  - Impure pad metals (>1%)
  - Poor hardness matching of bond pad and wire
  - Kirkendall voiding – differential diffusion
    - Au much better than Al

- **Process control:**
  - DOE of force and ultrasonic levels is key

- **Surface cleaning:**
  - Plasma cleaning substantially improves bond quality

Source: IPC/DPC – Bare Die (top); Sporian Microsystems (bottom)
Component Failure Mechanisms: Solder Bumps

- Key element: stable intermetallic between bump and base layer metal
- Bumps and BLM exposed to thermal/thermo-mechanical stresses and potential corrosion
- Voids from reflow process
- Intermetallic growth and fracture due to diffusion
- Surface migration between bumps

Source: Sony Products – Failure Mechanisms
Component Failure Mechanisms: Substrates

- Rapid evolution in substrate complexity driven by market
- Latest embedded structures pose additional challenges

Source: Blackshear, IBM, 2007

Source: Dudnikov, Sanmina, 2007
Component Failure Mechanisms: Substrate Examples

1. (a) Latent fiber defect
2. (c) Organic contamination
3. Via microcrack
4. Mechanical damage to Cu line
5. Unfilled via hole

Source: Liu et al., EDFAS, 2004
Component Failure Mechanisms: Solder Joints

- Acceleration model (Norris-Landzberg):

\[
AF = \left( \frac{\Delta T_{test}}{\Delta T_{field}} \right)^n \left( \frac{f_{field}}{f_{test}} \right)^{0.35} \cdot \exp \left( \frac{E_a}{k_b} \left( \frac{1}{T_{field}} - \frac{1}{T_{test}} \right) \right)
\]

- Thermo-mechanical fatigue of solder joints is one of the primary wearout mechanisms in electronic products
  - Possible changes due to Pb-free adoption: package dependent advantages over SnPb
  - Especially true in products used outside of commercial/consumer environments
    - Longer required lifetime
    - More severe operating conditions
Component Failure Mechanisms: Solder Joints -Solderability

- Solder
  - Contamination
    - Table 5-1 of IPC-ANSI J-STD-001D
  - Solder paste degradation/oxidation
    - Improper storage, excessive storage times
    - Uncontrolled assembly environment, excessive time on the screen
  - Defective flux
    - Insufficient activation

- Component
  - Inorganic contamination
    - Improper handling
  - Oxide formation
    - Improper storage, excessive storage times
  - Intermetallic formation
    - Insufficient plating thickness, improper storage, excessive storage times

- Printed board
  - Organic contamination
    - Solder mask (insufficient cure, misregistration)
    - Epoxy fill (insufficient cure)
  - Inorganic contamination
    - Improper handling
    - Plating residues
    - Non-optimized cleaning process
  - Oxide formation
    - Improper storage, excessive storage times
    - Contamination
  - Intermetallic formation
    - Insufficient plating thickness, improper storage, excessive storage times
  - Diffusion of copper base metal (nickel underplate only)
  - Black pad (immersion gold process only)

- Soldering process
  - Insufficient peak temperature
    - Failure to properly profile
  - Insufficient dwell above liquidus
A few words on a growing failure threat: Counterfeit Parts

- Any part or component that is not as represented
  - Duplication of another manufacturer’s product
  - Manufacturer’s product that failed test, inspection, or burn-in or was an engineering sample
  - Empty package or wrong functionality

- Parts being counterfeited include:
  - Newest parts & components
  - Obsolete parts
  - Inexpensive parts as well as high value parts
Top 4 Types of Counterfeits

- Used product marked as higher grade new product
  - These types of counterfeit parts may work, but will not operate at the same level as the higher grade part and may fail under stress that would be expected under normal conditions.
  - Electronics recycling or salvage sources

- Fake, non-working product
  - Disguised parts

- Defective Scrap
  - Inside sources

- New product re-marked as higher grade product
  - Like re-marked used product, re-marked new product will work, but not at the desired level of functionality.
Types of Confirmed Counterfeits

- **Microcircuits**
  - Microprocessors
  - Other Microcircuits
  - Memory
  - Radio Frequency/Wireless
  - Logic, Standard
  - Special Purpose Logic

- **Discretes**
  - Electromechanical
  - Thyristors
  - Capacitors
  - Other Discretes
  - Circuit Protection/Fuses
  - Diodes
  - Resistors
  - Sensors & Actuators
  - Optoelectronics
  - Power Transistors
  - Rectifiers
  - Small Signal Transistors
  - Magnetics
  - Crystals/Oscillators
Ceramic Capacitors (Thermal Shock Cracks)

- Due to excessive change in temperature
  - Reflow, cleaning, wave solder, rework
  - Inability of capacitor to relieve stresses during transient conditions.
- Maximum tensile stress occurs near end of termination
  - Determined through transient thermal analyses
  - Model results validated through sectioning of ceramic capacitors exposed to thermal shock conditions
- Three manifestations
  - Visually detectable (rare)
  - Electrically detectable
  - Microcrack (worst-case)
Thermal Shock Crack: Micro Crack

- Variations in voltage or temperature will drive crack propagation
- Induces a different failure mode
  - Increase in electrical resistance or decrease capacitance
Component Failure Mechanisms: Ceramic Capacitors & Flexure

- Excessive flexure of PCB under ceramic chip capacitor can induce cracking at the terminations
- Pb-free (SAC305) more resistant to flex cracking
  - Correlates with Kemet results (CARTS 2005)
- Rationale
  - Smaller solder joints
  - Residual compressive stresses
  - Influence of bond pad

![Graph showing Weibull distribution for SnPb and SnAgCu solder joints](image-url)

Reliability Analysis

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<th>F</th>
<th>S</th>
<th>(\beta_1)</th>
<th>(\eta_1)</th>
<th>(\rho)</th>
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<td>0</td>
<td>4.3551</td>
<td>1.6988</td>
<td>0.9831</td>
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</table>

Component Failure Mechanisms: Electrolytic Capacitors

- Liquid electrolyte is exposed to temperatures exceeding the boiling point
  - During reflow and rework

- Can result in
  - Case distortion (bulging)
  - Loss of seal
  - Failure of the capacitor
Component Failure Mechanisms: Al/Ta Polymer Capacitors

- Selected their volumetric efficiency (in larger case sizes)
  - Large capacitance values in small package
  - Very low ESR (equivalent series resistance)
- Susceptible to ignition due to high rush currents or other current spikes
  - Select fused capacitor
  - Consider current limiting resistor
- Aggressive derating required
  - Standard 50%
  - Higher derating at higher temperatures (>85°C) and certain circuits
Popcorning & Moisture Sensitivity Level (MSL)

- Popcorning controlled through moisture sensitivity levels (MSL)
  - Defined by IPC/JEDEC documents J-STD-020D and J-STD-033B
- Higher profile in the industry due to transition to Pb-free and more aggressive packaging
  - Higher die/package ratios
  - Multiple die (i.e., stacked die)
  - Larger components

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<td>72 hours</td>
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<td>48 hours</td>
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<tr>
<td>5a</td>
<td>24 hours</td>
</tr>
<tr>
<td>6</td>
<td>Time on Label (TOL)</td>
</tr>
</tbody>
</table>
Popcorning

- Moisture can be absorbed by polymeric material during transportation, storage and handling
  - Epoxy encapsulant
  - Die attach
  - Printed substrate
- Trapped moisture can experience sudden liquid-gas phase transition during reflow
  - Sudden volume increase due to vaporization
- Cracking and delamination – sometimes accompanied by popping sound
- Driven by package design, materials, storage conditions and reflow parameters
Popcorning in Tantalum/Polymer Capacitors

- **Pb-free reflow is hotter**
  - Increased susceptibility to popcorning
  - Tantalum/polymer capacitors are the primary risk

- **Approach to labeling can be inconsistent**
  - Aluminum Polymer are rated MSL 3 (SnPb)
  - Tantalum Polymer are stored in moisture proof bags (no MSL rating)
  - Approach to Tantalum is inconsistent (some packaged with dessicant; some not)

- **Material issues**
  - Aluminum Polymer are rated MSL 3 for eutectic (could be higher for Pb-free)
  - Sensitive conductive-polymer technology may prevent extensive changes

- **Solutions**
  - Confirm Pb-free MSL on incoming plastic encapsulated capacitors (PECs)
  - More rigorous inspection of PECs during initial build
Component Failure Mechanisms: Resistors

- Minimal variation when operated within specification
  - 0.5% at 70°C for 30 years
- Thin film and thick film resistors use laser trimming
  - Resistance adjustment
- Can induce hot spots during transient conditions
  - Power on, brown-outs, etc.
  - Up to 350°C
- Failure mode
  - Increase in resistance
- Two approaches
  - Obtain peak pulse guidelines
  - Design larger copper bond pads
Sulfide Corrosion of Thick Film Resistors

- Sulfur dioxide (SO$_2$) and hydrogen sulfide (H$_2$SO$_4$) in environment
  - Sources: Black rubber, industrial pollution
  - Attacks silver material under passivation/termination
  - Creates nonconductive silver sulfide

- Drivers
  - Cracking/separation of coating/termination
    - Poor manufacturing
    - Thermal shock
  - Potting or conformal coating
    - Seems to act as a ‘sponge’
    - Holds SO$_2$ molecules in place

- Electrical opens within 1-4 years

- Avoidance
  - Orient parallel to solder wave
    - Entrance side can experience thermal shock
  - Avoid hand soldering/rework
  - Sulfur-resistant PdAg material (KOA)
Predicting printed board damage can be difficult

- Driven by size (larger boards tend to experience higher temperatures)
- Driven by thickness (thicker boards experience more thermal stress)
- Driven by material (lower Tg tends to be more susceptible)
- Driven by design (higher density, higher aspect ratios)
- Driven by number of reflows

No universally accepted industry model
Component Failure Mechanisms: PCB Pad Cratering

- Cracking initiating within the laminate during a dynamic mechanical event (in circuit testing (ICT), board depanelization, connector insertion, shock and vibration, etc.)
- Drivers
  - Finer pitch components (only seen under solder balls)
  - More brittle laminates
- Difficult to detect using standard procedures
  - X-ray, Dye-n-pry, ball shear and ball pull
Component Failure Mechanisms: PCB Buckling

- **Definition:** excessive warpage of printed circuit board

- **Sources of increased stress:**
  - Non-parallel lamination fixturing/press platens
  - Absorption of moisture before assembly
  - Excessive temperatures during assembly
  - Rapid heating or rapid cooling during assembly
  - Bad fixturing during wave soldering

- **Causes of decreased strength:**
  - Incomplete cure of epoxy resin
  - Asymmetrical stackup of board layers
  - Unbalanced circuitry layers
  - Inadequate post-lamination stress relief
Component Failure Mechanisms: PCB Conductive Anodic Filaments (CAF)

- CAF also referred to as metallic electro-migration
- Electro-chemical process which involves the transport (usually ionic) of a metal across a nonmetallic medium under the influence of an applied electric field
- CAF can cause current leakage, intermittent electrical shorts, and dielectric breakdown between conductors in printed wiring boards
Component Failure Mechanisms: PCB Delamination

- Fiber/resin interface delamination occurs as a result of stresses generated under thermal cycling due to a large CTE mismatch between the glass fiber and the epoxy resin (1 vs. 12 ppm/°C).

- Delamination can be prevented/resisted by selecting resin with lower CTE’s and optimizing the glass surface finish.

- Studies have shown that the bond between fiber and resin is strongly dependent upon the fiber finish.
Component Failure Mechanisms: PCB Trace Peeling

- Delamination of trace from surface of the board

- **Sources of increased stress**
  - Excessive temperatures during high temperature processes
  - Insufficient curing of resin
  - Insufficient curing of solder mask

- **Sources of decreased strength**
  - Improper preparation of copper foil
  - Excessive undercut
Component Failure Mechanisms: Plated Through Holes (PTH)

- **Voids**
  - Can cause large stress concentrations, resulting in crack initiation.
  - The location of the voids can provide crucial information in identifying the defective process
    - Around the glass bundles
    - In the area of the resin
    - At the inner layer interconnects (aka, wedge voids)
    - Center or edges of the PTH

- **Etch pits**
  - Due to either insufficient tin resist deposition or improper outer-layer etching process and rework.
  - Cause large stress concentrations locally, increasing likelihood of crack initiation
  - Large etch pits can result in a electrical open
Component Failure Mechanisms: Plated Through Holes (PTH)

- **Overstress cracking**
  - CTE mismatch places PTH in compression
  - Pressure applied during "bed-of-nails" can compress PTH
  - In-circuit testing (ICT) rarely performed at operating temperatures

- **Fatigue**
  - Circumferential cracking of the copper plating that forms the PTH wall
  - Driven by differential expansion between the copper plating (~17 ppm) and the out-of-plane CTE of the printed board (~70 ppm)
  - Industry-accepted failure model: IPC-TR-579
Component Failure Mechanisms: PCB Electro-Chemical Migration (ECM)

- Defined, per IPC-TR-476A as the growth of conductive metal filaments or dendrites on or through a printed board under the influence of a DC voltage bias.
- Alternative definition:
  - Movement of metal through an electrolytic solution under an applied electric field between insulated conductors.
- Also known as dendritic growth.
- CAF is a subset of this mechanism.
- Electrochemical migration can occur on or in almost all electronic packaging:
  - Die surface
  - Epoxy encapsulant
  - Printed board
  - Passive components.

Elapsed time: 12 sec.
Electro-Chemical Migration: Details

- **Insidious failure mechanism**
  - Self-healing: leads to large number of no-trouble-found (NTF)
  - Can occur at nominal voltages (5 V) and room conditions (25°C, 60%RH)

- **Due to the presence of contaminants on the surface of the board**
  - Strongest drivers are halides (chlorides and bromides)
  - Weak organic acids (WOAs) and polyglycols can also lead to drops in the surface insulation resistance

- **Primarily controlled through controls on cleanliness**
  - Minimal differentiation between existing Pb-free solders, SAC and SnCu, and SnPb
  - Other Pb-free alloys may be more susceptible (e.g., SnZn)
Tin Whiskers - Definition

- Metallic crystal filaments that grow from tin-based materials
- First reported in 1946
- What do we know?
  - Tin whiskers come in lots of shapes
  - They can grow very long (>20mm)
  - More prevalent in plated tin than cast tin
  - More prevalent in ‘pure’ tin than tin alloys (with exceptions)
Tin Whiskers - Shapes

Highest aspect ratio
Longest length

Xu, Cookson
Electronics, IPC 2002
How do Tin Whiskers Cause Failure?

- **Direct Contact**
  - Causes an electrical short
  - Requires growth of sufficient length and in the correct orientation
  - Can lead to plasma arcing under vacuum

- **Electromagnetic (EM) Radiation**
  - Emits or receives EM signal and noise at higher frequencies
  - Deterioration of signal for frequencies above 6 GHz independent of whisker length

- **Debris**
  - Whisker breaks off and shorts two leads (primarily during handling)
ENIG Plating (Primary Issue)

- **Solder Embrittlement**
  - Not always black pad

- **Not explained to the satisfaction of most OEMs**

- **Numerous drivers**
  - Phosphorus content
    - High levels = weak, phosphorus-rich region after soldering
    - Low levels = hyper-corrosion (black pad)
  - Cleaning parameters
  - Gold plating parameters
  - Bond pad designs
  - Reflow parameters?

- **Results in a severe drop in mechanical strength**
  - Difficult to screen
  - Can be random (e.g., 1 pad out of 300)

- **Board fabricators need to be on top of numerous quality procedures to prevent defects.**
Other ENIG Failure Mechanisms

- **Insufficient nickel thickness**
  - Potential diffusion of copper through the nickel underplate
  - Can reduce storage time and number of reflow cycles

- **Bond pad adhesion**
  - Problem with corner balls on very large BGAs (>300 I/O)

- **Reduced plated through hole reliability (stress concentrators)**

- **Dewetting**

- **Crevice corrosion (trapped residues)**

- **Poor performance under mechanical shock / drop**
Sulfide Corrosion and Migration of Immersion Silver

- Failures observed within months
  - Sulfur-based gases attack exposed immersion silver
  - Non-directional migration (creepage corrosion)

- Occurring primarily in environments with high sulfur levels. Not recommended for these applications.
  - Rubber manufacturing
  - Waste treatment plants
  - Petroleum refineries
  - Coal-generation power plants,
  - Paper mills
  - Sewage/waste-water treatment
  - Landfills
  - Large-scale farms
  - Modeling clay
Failure Analysis Techniques

- Returned parts failure analysis always starts with Non-Destructive Evaluation (NDE)
- Designed to obtain maximum information with minimal risk of damaging or destroying physical evidence
- *Emphasize the use of simple tools first*
- (Generally) non-destructive techniques:
  - Visual Inspection
  - Electrical Characterization
  - Time Domain Reflectometry
  - Acoustic Microscopy
  - X-ray Microscopy
  - Thermal Imaging (Infra-red camera)
  - Superconducting Quantum Interfering Device (SQUID) Microscopy
Failure Analysis Techniques

- Destructive evaluation techniques
  - Decapsulation
  - Plasma etching
  - Cross-sectioning
  - Thermal imaging (liquid crystal; SQUID and IR also good after decap)
  - Surface/depth profiling techniques: SIMS-Secondary Ion Mass Spectroscopy, Auger
  - OBIC/EBIC
  - FIB - Focused Ion Beam
  - Mechanical testing: wire pull, wire shear, solder ball shear, die shear

- Other characterization methods
  - FTIR- Fourier Transform Infra-Red Spectroscopy
  - Ion chromatography
  - DSC – Differential Scanning Calorimetry
  - DMA/TMA – Thermo-mechanical analysis
Failure Analysis Techniques: Visual Inspection

- Rapid identification of:
  - Lot ID: was the sample covered by a previous corrective action? FA complete!
  - Counterfeit parts – increasingly prevalent problem throughout electronics industry
- Naked eye/magnifying glass/hand-held camera
  - Low cost, limited magnification
  - Results can be documented using a digital camera
  - Do not underestimate the value of this technique!
Visual Inspection: Lighting Options

- Room light is not the only option
- Backlight
  - Partially transparent samples (internal damage)
  - Silhouettes
- Ultraviolet
  - Detection of contamination, degradation of surface materials (conformal coating, solder mask, etc.)
Visual Inspection

- BGA (Ball Grid Array) Perimeter Inspection
  - Use of optical fiber to inspect solder balls on the perimeter of the package
  - Most common failure site under BGAs
  - Magnification: 200x
Visual Inspection: Examples

- **Charring**
  - Strongly suggests an electrical short
  - Exception: High voltage, where mechanical separation can result in arcing

- **Discoloration**
  - Metal: Suggests oxidation, corrosion, or microstructural evolution due to thermal event
  - Polymer: Indication of contamination or damage due to thermal event

- **Solder wetting**
  - Extent of coverage
  - Shape (convex vs. concave)

- **Other issues**
  - Debris, surface damage (scratches)
  - Component cracking/deformation
Optical Microscopy

- Magnifies objects by the bending of light through shaped lenses
  - Eyepiece
  - Objective
- Maximum magnification is limited by the wavelength
  - Natural light (0.4 to 0.7 microns)
  - 0.2 micron limit of resolution
- Benefits:
  - Ease of use
  - Wide range of magnification
  - Digital imaging: 3X resolution increase
- Disadvantages:
  - Resolution limit
  - Limited depth of focus
- Confocal microscopy extends range of optical microscopy: depth scanning
Stereomicroscopy: Lighting

- Lighting also important here
- Light source
  - Different spectra create different coloration
  - Halogen, fluorescent, light emitting diodes (LEDs)
- Directionality
  - Influences degree and orientation of shadowing
  - Critical for tin whisker detection
  - Ring light (annular light), fiber-optic light

Halogen highlights reds
Fluorescent highlights blues
Electrical Characterization

- Most critical step in the failure analysis process
  - Can the reported failure mode be replicated?
    - Persistent or intermittent?
    - Intermittent failures often incorrectly diagnosed as no trouble found (NTF)
  - Least utilized to its fullest extent
  - Equipment often shared with production and R&D

- Approach dependent upon the product
  - Component
  - Bare board
  - PCB assembly

- Sometimes performed in combination with environmental exposure
  - Characterization over specified temperature range
  - Characterization over expected temperature range
  - Humidity environment (re-introduction of moisture)
  - Not designed to induce damage!
Electrical Characterization: Components

- **Most critical step in the failure analysis process**
  - Can the reported failure mode be replicated?
  - Persistent or intermittent?
  - Intermittent failures often incorrectly diagnosed as no trouble found (NTF)
  - Least utilized to its fullest extent
  - Equipment often shared with production and R&D
  - For best results, a *known good reference sample* is required.

- **Parametric characterization**
  - Comparison of performance to datasheet specifications

- **Curve tracer**
  - Applies alternating voltage; provides plot of voltage vs. current response
  - Valuable in characterizing diode, transistor, and resistance behavior

- **Time domain reflectometry (TDR)**
  - Release and return of electrical signal along a given path
  - Measurement of phase shift of return signal indicates potential location of electrical open

- **Other characterization equipment**
  - Inductance/capacitance/resistance (LCR) meter
  - High resistance meter (leakage current < nA)
  - Low resistance meter (four wire; < milliohms)
Curve Tracing – Counterfeit Example

- Some limitations of physical characteristic testing
  - Parts may be re-manufactured or factory rejects in what appears to be authentic packaging
  - No conclusive identification information on the die once decapsulated
- Therefore, some electrical analysis is helpful in determining authenticity.
  - Although full datasheet testing is highly recommended for high reliability applications, a curve trace on each lead is a very effective way to begin an electrical examination of the parts.
  - A known good or reference component is required.
Electrical Characterization: Bare Board

- In-circuit testing (ICT)
  - Primarily performed on in-line failures (bed of nails or flying probe)
  - Detection of electrical opens and shorts
    - Based on triggering rules (pass/fail)
  - Allows for relatively accurate identification of failure site

- Time domain reflectometry (TDR)

- Resistance measurements (manual)
  - Binary approach

- Environmental stresses
  - Electrical short (temperature/humidity)
  - Electrical open (temperature cycling)
  - Requires continuous monitoring (intermittent behavior)
Electrical Characterization: PCB Assembly

- **Functional**
  - Most valuable, if product is experiencing ‘partial’, permanent failure

- **JTAG (joint task action group) boundary scan**
  - Allows for testing ICs and their interconnections using four I/O pins (clock, input data, output data, and state machine mode control)
  - Allows for relatively accurate identification of failure site, but rarely performed on failed units (primarily replacement for In Circuit Test-ICT)

- **Oscilloscope**
  - Measures voltage fluctuations as a function of time (passive)
  - Useful in probing operational circuitry
  - Digital capture provides better documentation capability
  - Available stand alone or PC-based

- **Isolation of attached components**
  - Attempt to perform as much electrical characterization without component removal
  - Consider trace isolation (knife, low speed saw)

- **Environmental stresses**
  - Approach similar to bare board
Higher Risk Non-Destructive Evaluation (NDE)

- NDE sometimes carried out in a semi-automated manner
  - All incoming failures subject to the same series of NDE processes
  - Important to understand that NDE equipment is not completely non-destructive

- Thermal imaging
  - Temperature rise can damage or mask fragile conductive filaments (joule heating, thermal runaway, evaporation of retained moisture)

- Acoustic microscopy
  - Can remove residues/contaminants when product is submerged in water
  - Selection of bath fluid is key (distilled/deionized water; IPA; oil; etc.)

- X-ray microscopy
  - Elevated exposure, especially with laminography, can induce damage in sensitive components (EEPROM)

- SQUID microscopy
  - Sensitivity allows for use of very low voltages; most non-destructive
Thermal Imaging

- Thermography is the use of an infrared imaging and measurement camera to "see" and measure thermal energy emitted from an object.
  - Provides precise non-contact temperature measurement capabilities.
  - Spectral range can be broken into one of four ranges, near IR: 0.75-3 microns, middle IR: 3-6 microns, far IR: 6-15 microns, and extreme IR: 15-30 microns.

- Important parameters include measurement temperature range, spectral range, accuracy, resolution, and steady state vs. real-time
  - Resolution for PCBA: 15 microns
  - Resolution on-die: 1 micron

- Excellent for:
  - Electrical shorts
  - Power components
Thermal Anomalies Detected

- Q16 producing heat when it is supposed to be in an off state - sneak circuit detected
- D11 detected a hot spot that exceeded thermal limit

Resulted in overheating nearby capacitors
Acoustic Microscopy

- Method for inspecting internal structures through the application of high frequency (>20 kHz) sound waves
- Requires immersion in water (acoustic signals reflected by air)
  - Allows for very accurate detection of voids and delaminations
- Options
  - Frequency
  - Transmission mode
  - Imaging
Acoustic Microscopy: Transducer Frequency

High frequency
Short focus

1. Higher resolution
2. Shorter focal lengths
3. Less penetration
   (Thinner packages)

Low frequency
Long focus

1. Lower resolution
2. Longer focal lengths
3. Greater penetration
   (Thicker packages)

General rules:
- **Ultra High Frequency** (200+ MHz) for flip chips and wafers.
- **High Frequency** (50-75 MHz) for thin plastic packages. (110MHz-UHF) for flip chips.
- **Low Frequency** (15-30 MHz) for thicker plastic packages
Acoustic Microscopy: Transmission Mode

**Pulse-Echo**
- Uses ultrasound reflected from the sample
- Can determine which interface is delaminated
- Requires scanning from both sides to inspect all interfaces
- Provides images with high degree of spatial detail
- Peak amplitude, time of flight (TOF), and phase inversion measurement

**Through Transmission: Two Transducers**
- Uses ultrasound transmitted through the sample
- One scan reveals delamination at all interfaces
- No way to determine which interface is delaminated
- Less spatial resolution than pulse-echo
- Commonly used to verify pulse-echo results
Acoustic Microscopy Imaging

Through transmission

Peak amplitude image of die top

Phase inversion image of die top

Peak amplitude image of die attach

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Acoustic Microscopy

- Used when delamination or voiding is suspected
  - Electrical shorting within the package (delamination, electro-chemical migration)
  - Electrical opens (delamination, wire bond failure)
  - Insufficient thermal performance detected (i.e. die attach)
  - A known good reference sample is desirable

- Some value for ceramic BGAs
  - Attenuation due to multiple interfaces prevents imaging of interconnects under PBGAs
Typical Acoustic Microscopy & X Ray

Acoustic Microscopy Equipment

X-Ray Inspection Equipment
X-Ray Microscopy

- Allows for internal inspection through the use of X-ray energy
- Latest innovations
  - Digital detectors
  - Laminography (‘virtual’ cross-sectioning)
    - 3D reconstruction
  - Nanofocus resolution
  - Oblique viewing
X-Ray Microscopy

- Digital detector
  - Provides greater contrast through wider range of grayscale (elemental differentiation)
  - Prerequisite for 3-D imaging

- Laminography
  - Provides X-ray sectional images and slice in any direction as well as three-dimensional visualizations of the specimen

- Types of laminography
  - Agilent 5DX
    - Best setup for inline inspection; moderate FA capabilities
  - Everyone else (computed tomography)
    - Allows for ‘virtual cross sectioning’ and 3-D reconstruction
    - Requires rotation of the sample (limited sizing) and extensive exposure time

- Resolution
  - Sub-micron

- Oblique viewing
  - Increases capability of 2-D viewing
  - 60 to 80 degree capability
X-Ray Inspection – Counterfeit Example

- Inspect for:
  - Extra wire bonds
  - Wrong configuration of bond pads
  - Larger die than expected
  - Extra heat capacity (large paddle)
SQUID Microscopy

- Current flow in devices produce a magnetic field
  - SQUID uses a highly sensitive magnetic detector (superconductor) to resolve these fields
  - Magnetic field image is converted to a current density image, allowing for fault location

- Resolution
  - 500 nA, 300 nm
  - Dependent on working distance (requires a flat sample)
SQUID Microscopy

- Critical technology for detecting package level electrical shorts
  - Much more rapid failure site resolution
  - Absolute confirmation of shorting path
  - Thermal imaging induces damage
  - A known good reference sample is desirable.
SQUID Microscopy

- Extremely effective in locating failure site
Decapsulation

- **Note:** point of no return! Voids any warranties

- **Mechanical preparation and removal**
  - Non-critical material adjacent to die removed with diamond wheel
  - Gross package removal with razor blades, carbide/diamond drill bits, and polishing wheels
  - Stop once the tips of the wirebonds are contacted: electrical testing possible

- **Chemical removal**
  - **Warning:** significant safety precautions and training required
  - Methods: heated sample + dropper application or immersion
  - Fuming nitric acid: apply, rinse in IPA, ultrasonic rinse with methanol
  - Fuming sulfuric acid: apply, ultrasonic rinse in DI water and then methanol

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<th>Nitric</th>
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<td>Silicone die coating</td>
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Source: Wills et al., Microelectronics Failure Analysis
Common Decap Equipment
Common Etching Equipment

Wet Etch Tanks

Plasma Etchers
Cross-Sectioning

- Standard method for destructive subsurface evaluation

- Method:
  - Cleaving/sawing to approximate area of interest
  - Potting in epoxy resins to aid polishing
  - Polishing medium dependent upon materials: typically diamond, SiC, or alumina suspensions & embedded polishing cloths
  - Coarse to fine (600 grit to 0.05 um) grinding sequence to eliminate damage from previous step
  - Final etch often used for microstructural relief
  - Optical/electron microscopy techniques used for inspection thereafter

- Used to isolate single IC layers for defect inspection
- Top surface optical/SEM images can be correlated with top or bottom surface thermal/electrical/optical images (see subsequent techniques)
- Special fixtures and chemical and mechanical polishing (CMP) methods used for maintaining parallelism
Typical Cross Sectioning Equipment

Inverted Microscope

Polishing & Grinding Disks

Precision Saw

Specimen Mounting

Polishing Compounds, Epoxies

Polishing and Grinding Equipment
Decapsulation and Cross Sectioning: Counterfeit Example

- Allows direct inspection of circuits and identification of:
  - Extra circuitry
  - Extra layers
  - Extra interconnects
Scanning Electron Microscopy

- Sample rastered with an electron beam
- Emitted electrons sorted by delay and quantity
Scanning Electron Microscopy

Secondary electron detection yields topographic information
Backscattered electron detection also used for topography and elemental analysis
Most surface techniques rely on energy signatures reflected, transmitted, or emitted when a particular atom or molecule is bombarded with electrons, x-rays, or IR radiation.
Energy Dispersive X-Ray Spectroscopy (EDS)

- Used with SEM
- X-ray emission signature from electron source
- Elemental analysis of solid samples
- Identification based on multiple emission lines (K, L, M)
- Can’t detect light elements: H, He, Li, Be
- Emission from subsurface “tear drop”

EDS scan of elemental copper

Monte Carlo simulation of Si K-α X-rays in an SiO2 matrix at 5 keV (Vanderlinde, 2004)
X-Ray Fluorescence Spectroscopy

- X-ray emission signature from x-ray source
- Portable models now available
- Crystallographic analysis of solid samples
X-Ray Fluorescence (XRF) Analysis

- X-ray fluorescence widely used to determine the elemental composition of the components and to determine the lead content for compliance to the RoHS directive.
- A new use for XRF to compare a known good component to a suspect component by comparing the elements of the leads as well as the packaging.
- Software developed to compare the two in order to assist in authenticity verification.
Auger Spectroscopy

- Emission from top few monolayers
- Provides chemical concentration and bonding state information
- Depth profiling capability – excellent for coatings and surface contamination

Contamination on metal lines

Source: Scherer et al., Microelectronics Failure Analysis, 2004

Peak energy variation for C in SiC and graphite
Secondary Ion Mass Spectroscopy (SIMS)

Quadrupole dynamic SIMS

- Two types:
  - Static (low current, low surface perturbation)
  - Dynamic (high surface perturbation; depth profiling)
- Highest resolution of surface techniques
- Excellent for assessing doping concentrations and multi-layer structures

Laser diode failure analysis

Source: Mount et al., Microelectronics Failure Analysis, 2004
Ion Chromatography

- Chromatography is a method for separating mixtures of substances using two phases, one of which is stationary and the other mobile moving in a particular direction.

- The term “ion chromatography” covers all rapid liquid chromatography techniques for separation of ions in columns coupled with detection and quantification in a flow-through detector.

- Chromatography techniques are divided according to the physical states of the two participating phases; the term “ion exchange chromatography” or “ion chromatography” (IC) is a subdivision of high performance liquid chromatography (HPLC).
**Ion Chromatography: Method**

- A stoichiometric chemical reaction occurs between ions in a solution and a solid substance carrying functional groups that can fix ions as a result of electrostatic forces.
  - In anion chromatography these are quaternary ammonium groups; in theory, ions with the same charge can be exchanged completely reversibly between the two phases
  - The process of ion exchange leads to a condition of equilibrium; the side to which the equilibrium lies depends on the affinity of the participating ions to the functional groups of the stationary phases

- A known amount of analyte is passed through the stationary phase column by the mobile phase eluent
  - The retention time for each species of ion or charged molecule is determined by its charge state and atomic size
  - The conductivity measured as each species pass through the detector is proportional to its concentration
Ion Chromatography: Results
Cleanliness Controls: Ion Chromatography

- Contamination tends to be controlled through industrial specifications (IPC-6012, J-STD-001)
  - Primarily based on original military specification
  - 10 µg/in² of NaCl ‘equivalent’
  - Calculated to result in 2 megaohm surface insulation resistance (SIR)
  - Not necessarily best practice

- Best practice is contamination controlled through ion chromatography (IC) testing
  - IPC-TM-650, Method 2.3.28A

<table>
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<th>General Electric</th>
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</tr>
</tbody>
</table>

*Based on R/O/I testing
Some Simple Debug Tools to consider

- **Portable Preheater:**
  - Allows for controlled rework/repair/replacement at a debug bench
  - [http://www.zeph.com/airbat hseries.htm](http://www.zeph.com/airbat hseries.htm)
Temperature Tools

- Cold Spray and hot plates to simulate fails at temperature extremes
Temperature Indicating Labels/Strips

- Temperature and humidity strips and labels are simple, inexpensive, and easy to use
Refillable Flux/Liquid Pen

- Allows for controlled application of fluxes, cleaners, and other liquids
- [http://www.startinternational.com/prodsumm.asp?id=34&type=cat&level=1](http://www.startinternational.com/prodsumm.asp?id=34&type=cat&level=1)
Flexible Light Sources & Mirrors

- Make it easier to look under and around areas on an assembly
- [http://minimicrostencil.com/mini_mirror.htm](http://minimicrostencil.com/mini_mirror.htm)
- [http://www.metronusa.com/mirrors1.htm](http://www.metronusa.com/mirrors1.htm)
Dye N Pry Capability

- Allows for quick (destructive) inspection for cracked or fractured solder joints under leadless components (BGAs, BTCs)

Dremel Tool – Induce Vibrations

- A Dremel tool can be used to induce local vibration during debugging
- http://www.dremel.com
Contact Information

Questions:

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- askdfr@dfrsolutions.com
- www.dfrsolutions.com

Connect with me in LinkedIn as well!