Basics of Failure Analysis

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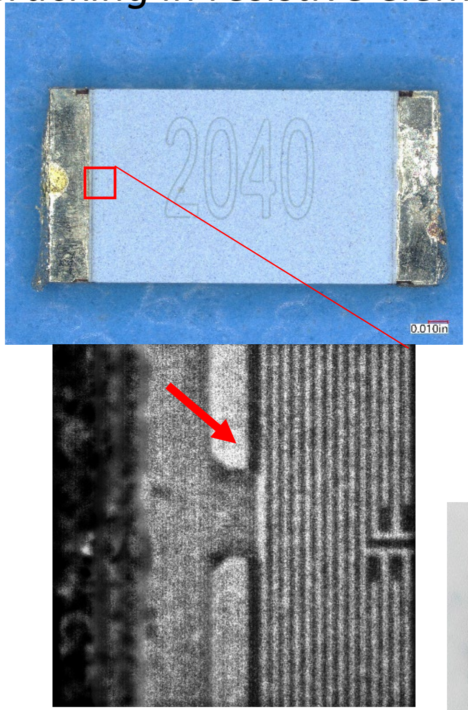
Acronyms

Abbreviation	Definition	Abbreviation	Definition
%v	Percent volume	MOSFET	Metal-oxide-semiconductor field-effect transistor
Ar	Argon	N2	Nitrogen
CA	Construction Analysis	NASA	National Aeronautics and Space Administration
CO	Carbon monoxide	NH3	Ammonia
CO2	Carbon dioxide	O2	Oxygen
CSI	Customer source inspection	OBIRCH	Optical Beam Induced Resistance Change
DPA	Destructive Physical Analysis	PIND	Particle Impact Noise Detection
EBAC/EBIC	Electron Beam Induced Current / Electron Beam Absorbed Current	PN	Part Number
EDS	Energy Dispersive Spectroscopy	Ppm	Parts per million
EEEE	Electrical, Electronic, Electromechanical, and Electro-optical parts	ppmv	Parts per million volume
EOS	Electrical Overstress	SAE	(formerly) Society of Automotive Engineering
ESD	Electrostatic Discharge	SDR	Space-Domain Reflectometry
FA	Failure Analysis	SEI	Seebeck effect imaging
FC	Fluorocarbons	SEM	Scanning Electron Microscope
FIB	Focus ion mill	Si	Silicon
GMR	Giant Magneto-Resistor	SMD	Surface mount device
GSFC	Goddard Space Flight Center	SnPb	Tin lead
He	Helium	SQUID	Superconducting quantum interference device
IGA	Internal Gas Analysis	TDDB	Time Dependent Dielectric Breakdown
IR	Infrared	TEM	Transmission electron microscope
JFET	Junction Field Effect Transistor	TIVA	Thermally induced voltage alteration
Kr85	Krypton 85	um	Micrometer
		XIVA	External induced voltage alteration

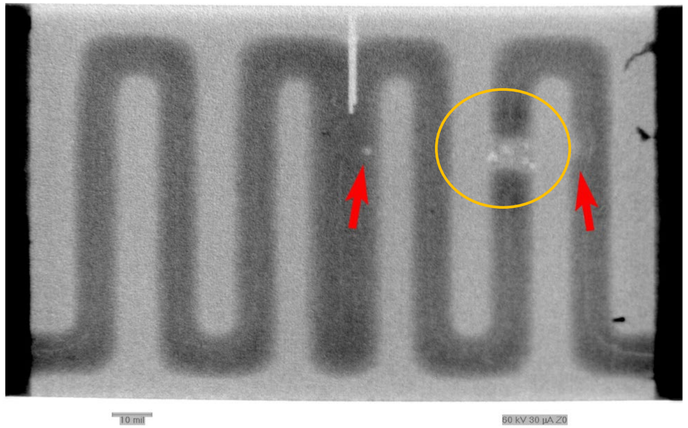
How different professions view a part

- To a designer 
- To a parts engineer reading bill of materials: *Resistor Film 1206 100 Ohm 1% 0.25W(1/4W) ±100ppm/°C 0.01% SMD*
- To a failure analyst a part is a collection of failure mechanisms waiting to happen

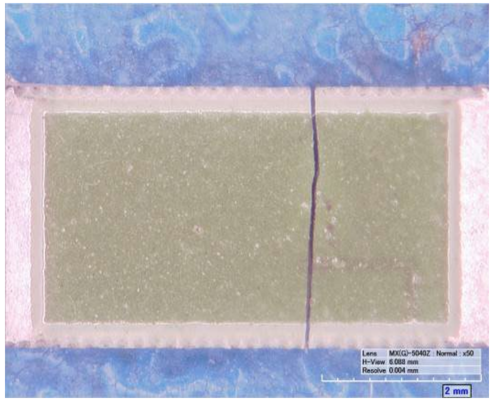
Cracking in resistive element



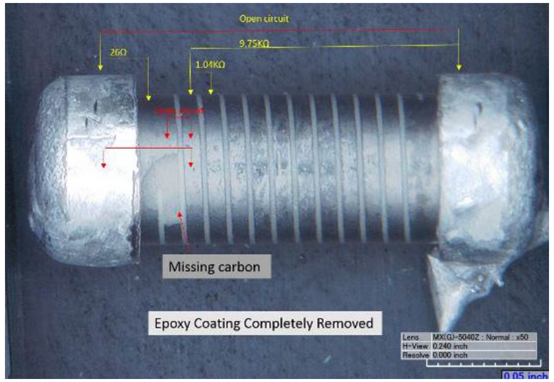
Fusing open of resistive element



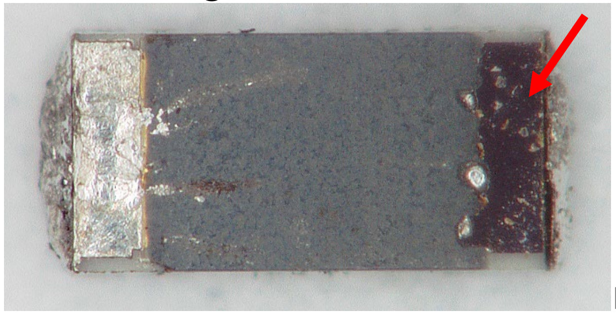
Cracking in ceramic substrate



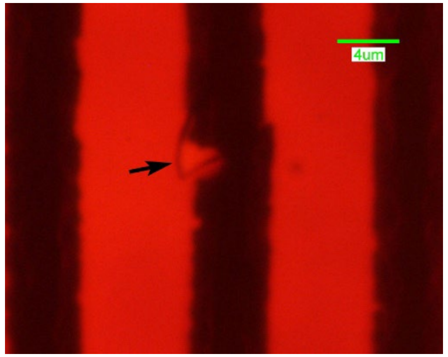
Separation of resistive element



Missing end termination



Particle embedded in resistive element

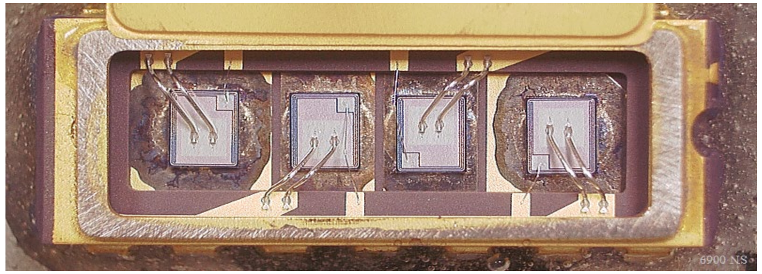


Content

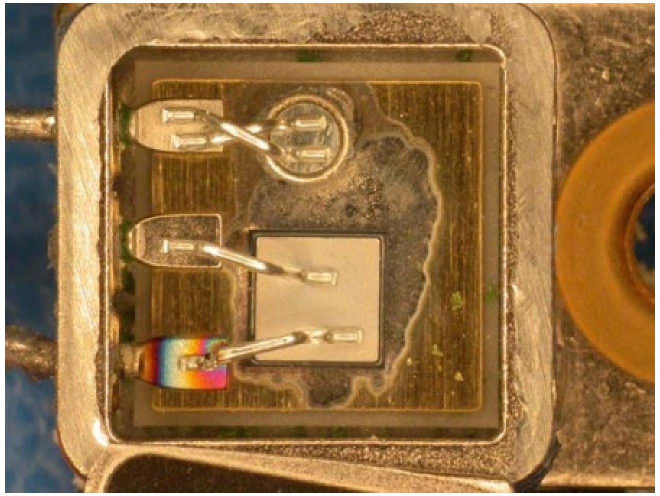
- Failure analysis definitions
- Typical flow of failure analysis
- Description of common failure analysis techniques
- Failure Modes and Mechanisms
- A few things I wish I knew
- A gallery of failures
- Attributes of a good failure analyst

What Failure Analysis Is and What it is Not

- Failure Analysis – process of examining data and physical evidence related to EEEE part failure to meet its intended function
- What Failure Analysis does not cover
  - Destructive Physical Analysis (DPA)
    - DPA is defined for space industry by MIL-STD-1580, NASA GSFC S-311-M-70 or similar document
    - DPA is intended to look at workmanship of incoming parts to assess their quality, identifying manufacturing anomalies
    - DPA follows a prescribed formula of tests from external and non-destructive to internal destructive
  - Construction Analysis (CA)
    - CA is the process of examining EEEE part construction to understand its design, materials, and identify flaws that may lead to failures during use
    - CA is a term more generic than DPA, where additional steps may be recommended that are not covered by DPA specs
    - There are no clearly defined criteria for determining pass/fail of anomalies, and they must be dispositioned by cognizant engineers
  - Root Cause Analysis
    - Identification of processes and events that led to a failure with the intent of mitigating future failures
    - Failure analysis can be a part of root cause analysis

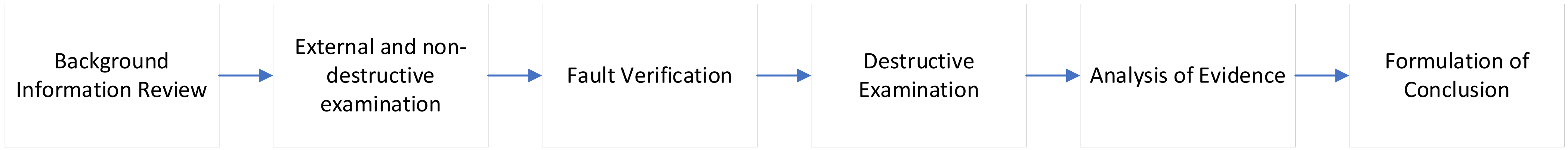


Destructive Physical Analysis



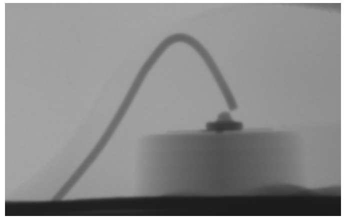
Failure Analysis

Typical Flow of Failure Analysis



- Level of effort vary by customer - some customers are satisfied by verification of failure, while others require detailed recreation of events
- Some failure analyses may end earlier, when the desired conclusion was reached
- Some failure analyses will require iterations, when based on findings, additional techniques are called upon
- Occasionally, the damage is so egregious, that original failure likely is gone
  - Ideally, a representative sample can be subjected to similar stresses to recreate a failure and propagation of damage can be stopped in time to analyze

Failure Analysis Techniques

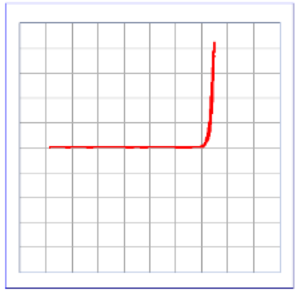


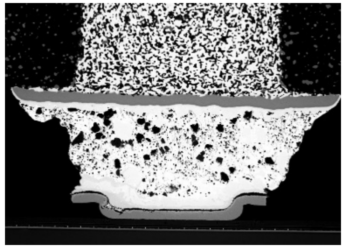
External Non-destructive Analysis

- Optical Microscopy (Bright field, dark field, vicinal illumination)
- Scanning Acoustic Microscopy
- X-Ray (2D and 3D)

Electrical Fault Verification

- Curve tracing
- Functional Testing
- Micro- or nano-probing



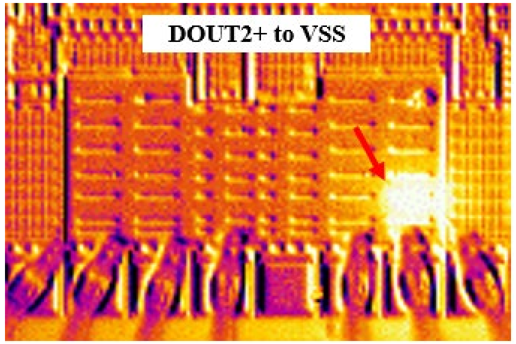


Destructive Examination

- Cross-sectioning
- De-lidding
- Decapsulating (chemical, laser, plasma)
- Ion Milling
- Wire pull/ Ball shear
- Internal Gas Analysis

Analysis of Evidence

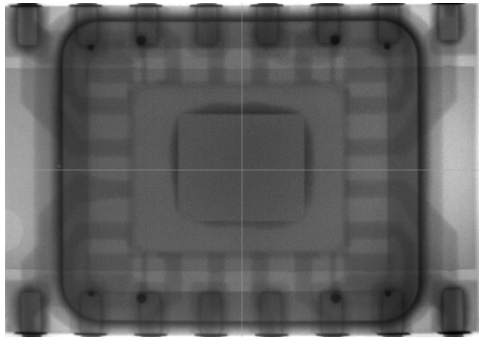
- Optical
- Infrared imaging
- SEM/EDS
- FIB
- TEM
- Electron Beam Stimulation (EBAC/EBIC)
- Thermal laser stimulation (OBIRCH, TIVA, XIVA, SEI)
- Magnetic Imaging (SQUID, SDR, GMR)



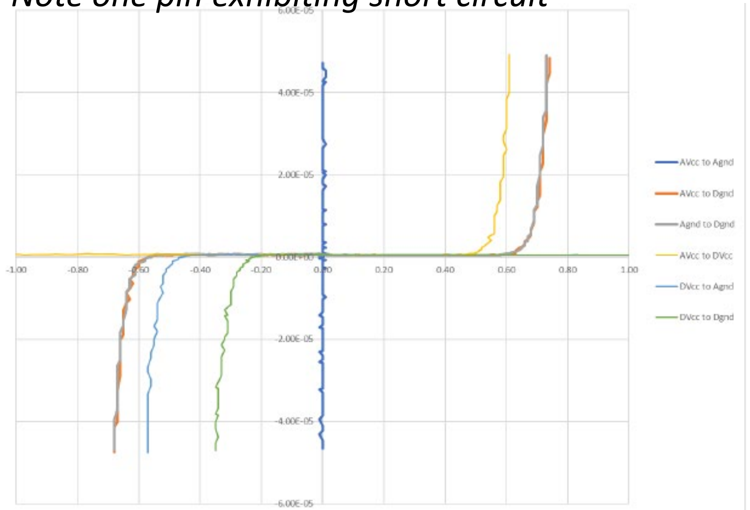
Example of Failure Analysis Flow

- Background:
  - Microcircuit exhibits an unexpected short circuit between supply and ground pins
- External and nondestructive examination:
  - Optical microscopy and X-Ray show no anomalies with the package or internal assembly
- Fault Verification:
  - Curve tracing confirms short between supply and ground
- Destructive examination:
  - Delidding of device, followed by optical and SEM examination show no evidence of damage on surface of die
- Additional Analysis:
  - Magnetic Current Imaging points to short circuit path between ground and power.
  - Delayering the part showed electrical overstress (EOS) under the bond pad for power wirebond

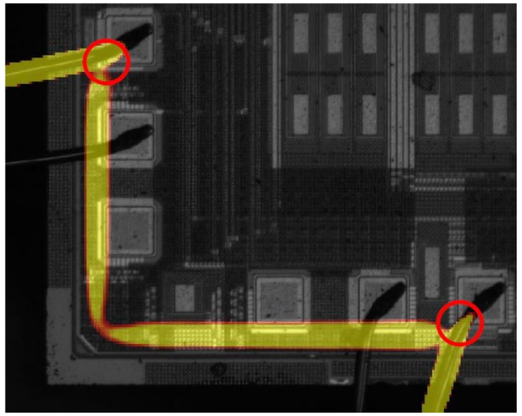
X-Ray shows no anomalies



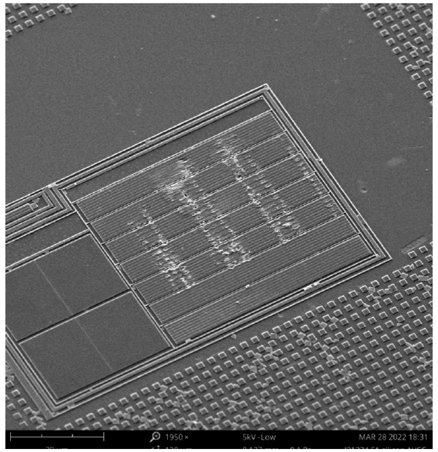
Current-Voltage plots of pin-to-pin curve tracing. Note one pin exhibiting short circuit



Magnetic current imaging showing shorting path



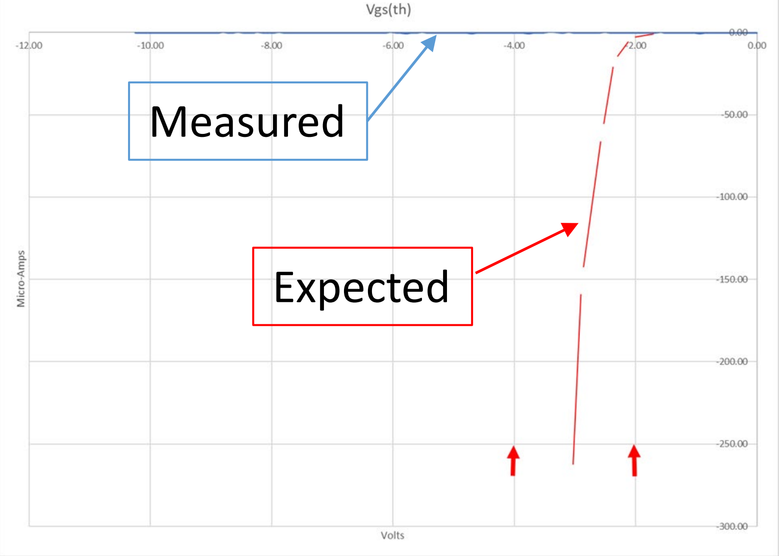
SEM of Electrical Overstress under the bond pad



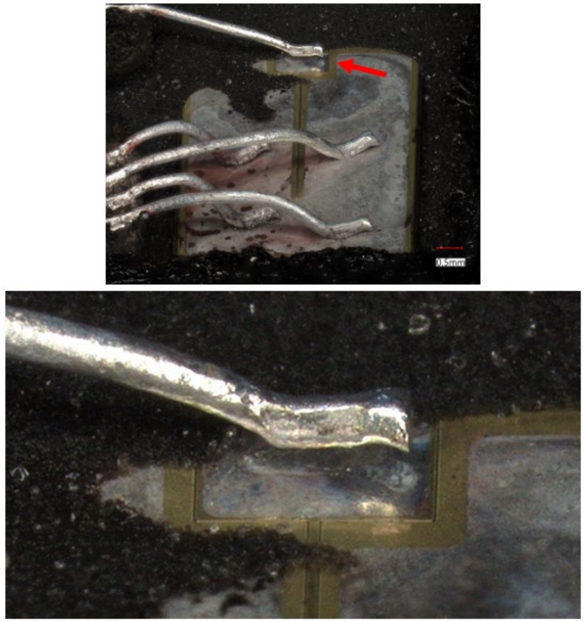
A note on Failure Mechanisms and Modes

- Failure Mode – the anomalous behavior of a part
  - Example: Open circuit, short circuit, intermittent electrical contact, parametric shift beyond specification
- Failure Mechanism – the physical manifestation of failure
  - Example: Gate is open circuit leading to no voltage output of a transistor
  - Better example: Gate is open circuit due to gate wire lifting from the die, leading to no voltage output of a transistor
  - Even better example: Insufficient stress relief in the gate wire resulted in lifting of wire, leading to no voltage output of a transistor

Failure Mode:
Current-Voltage plot showing open circuit of a transistor



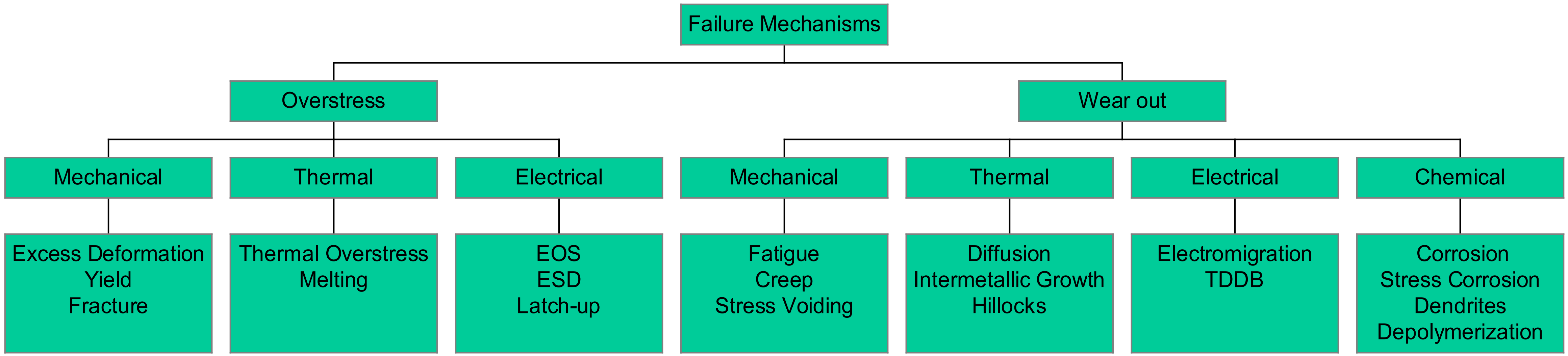
Failure Mechanism:
Lifting of gate wire from the die



Source: NASA GSFC J23288

Failure Mechanism Categories

Failure Mechanisms in Products

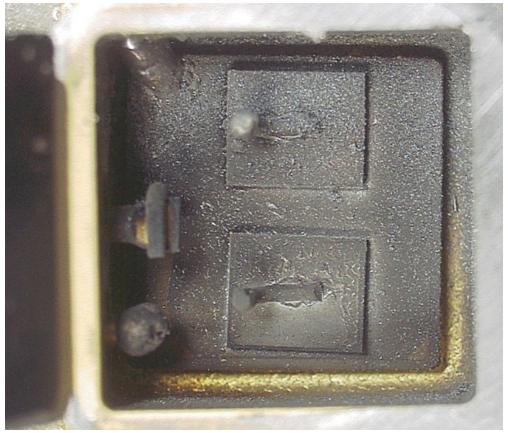


- After Pecht, Dasgupta, Evans and Evans, 1994

Failure Mechanism: Overstress Examples

Electrical

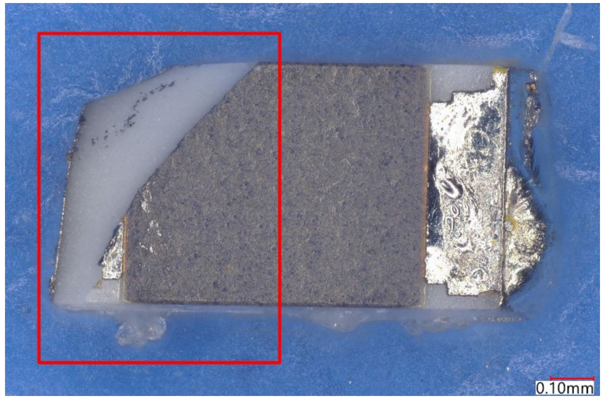
Failure mode: Open circuit of transistor
Failure mechanism: Transistor showed open circuit due to internal aluminum wires exposed to very high current



Internal visual examination of failed transistor showing open aluminum wires, and aluminum coating the inside of the device

Mechanical

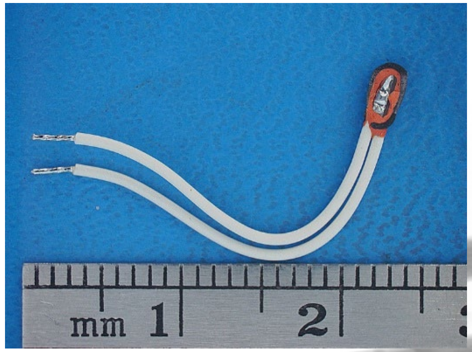
Failure mode: Open circuit of resistor
Failure mechanism: Fracture of resistor



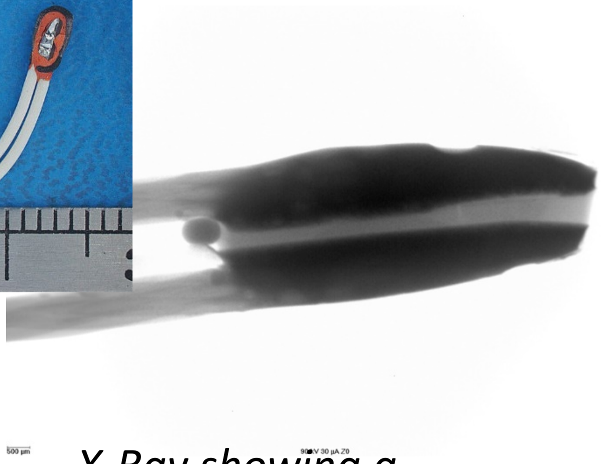
Optical image showing missing end termination of resistor

Thermal

Failure mode: Short circuit of thermistor
Failure mechanism: Internal solder reflowed and shorted across the internal pellet



Thermistor as-received for FA

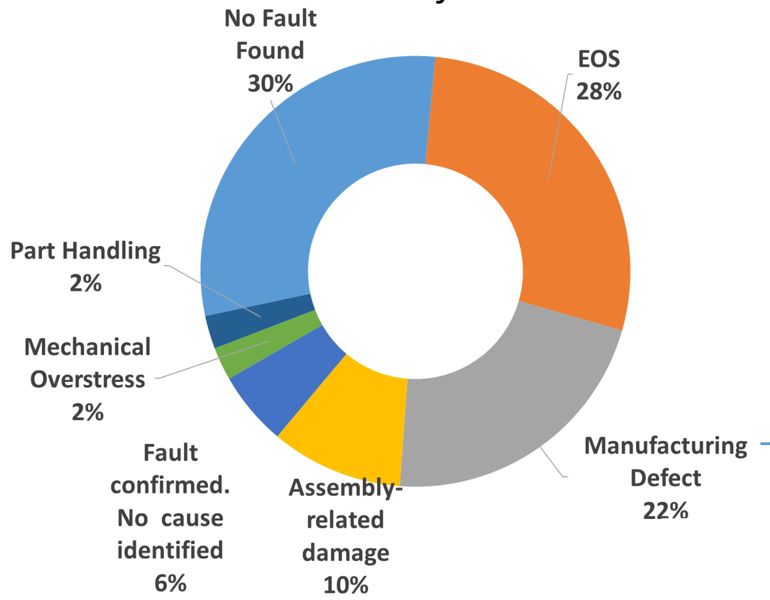


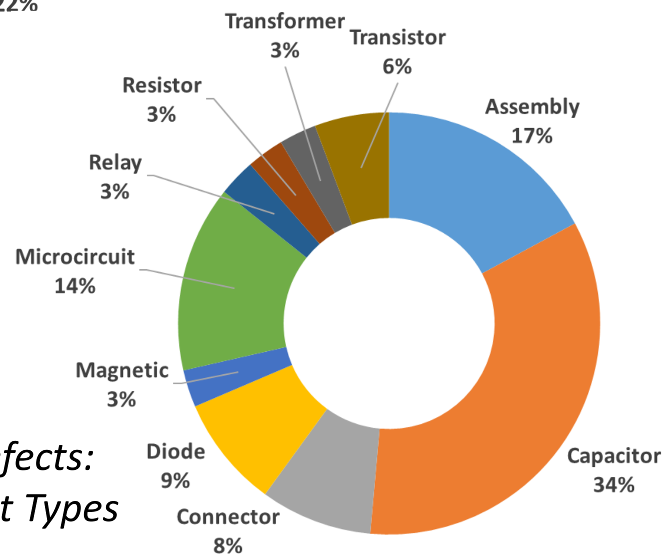
X-Ray showing a solder ball

NASA GSFC Statistics of FAs for 2017-2024*

(*) stats for 2024 are incomplete

Breakdown of FA conclusions





Manufacturing Defects: Breakdown by Part Types

- Perform 20-30 failure analyses (FA) per year, mostly for NASA GSFC projects
- FA is usually requested when EEE part has been identified as suspect or faulty during assembly inspection or testing
- Most common EEEE parts submitted for FA:
  - Microcircuits - 34%
  - Capacitors - 17%
  - Hybrids - 9%

Most common failure categories:

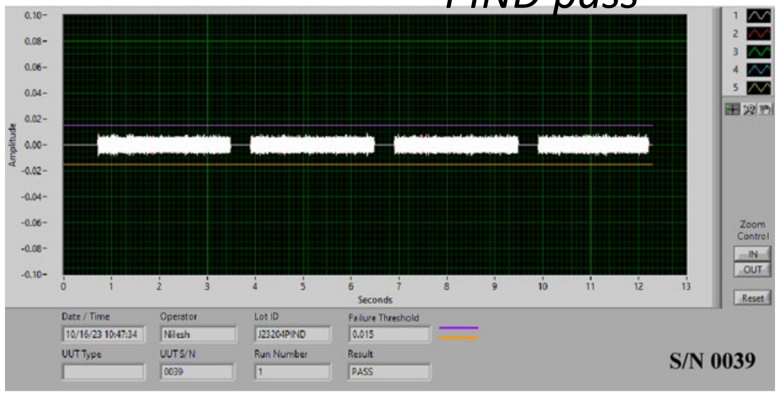
- Electrical Over Stress (EOS) – 28%
  - Lumping ESD and EOS together for this statistic
- Manufacturing Defects – 22%
  - Most devices with manufacturing defects that come to FA are capacitors

A few things I wish I knew before learning the hard way

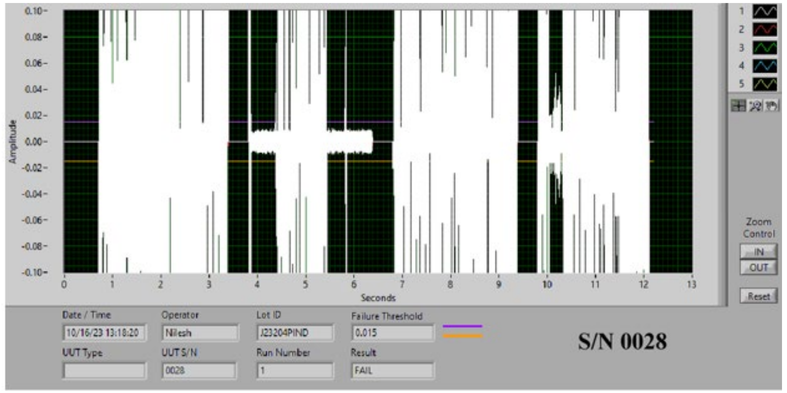
Particle Impact Noise Detection (PIND)

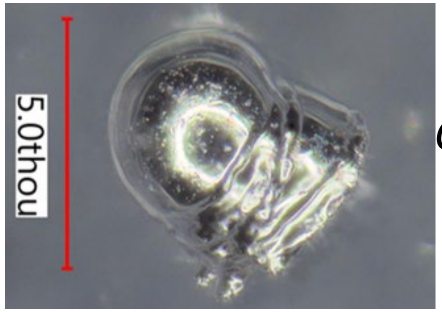
- Particle Impact Noise Detection (PIND) is used to identify particles inside the cavity devices
- Screening for parts with particles inside prevents two types of failures
  - Failures in space, where a stray particle may float in zero-g environment and may settle to short between closely spaced conductors
  - Failures in high vibration and mechanical shock where such actions may induce particles to move within a package increasing likelihood of undesirable consequences (e.g., short circuit for electrically conductive particles or impeding movement of moveable objects in relays or blocking electrical conduct if non-conductive particles
- PIND failure is usually followed by particle capture, where a small hole is carefully drilled through the body of the part and covered by tape, then the part is shaken to allow particle to bounce around and be caught on the tape
- Not very common in Failure Analysis, since aggressive shaking may dislodge a particle that is already causing a short

PIND pass



PIND Fail





Captured Particle

Internal Gas Analysis (IGA)

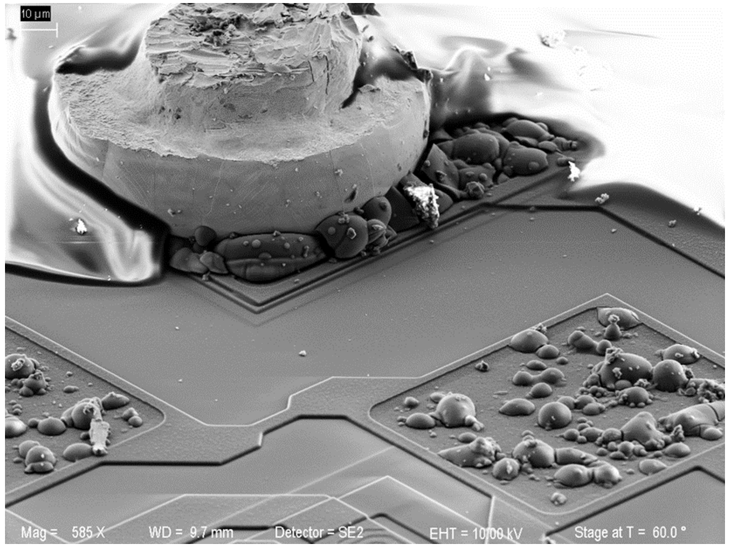
- Internal Gas Analysis (IGA) is used only on cavity devices
- Performed by puncturing the device, collecting internal gas, and analyzing on a mass spectrometer, binning volatile species by their molecular weight
- Lab performing the testing will typically provide results in %v, where only gases being examined for will be accounted for up to 100%v
  - Some molecular weights are lumped together to report a generic category, such as fluorocarbons (FC)
  - The analysis is comprehensive for most packages, but can be confusing if some species of importance are not reported in a standard report
- Where gases come from:
  - Seal gases: ~100%v N2, 90%v/10%v N2/He, dry air (80%v N2, 19%v O2, 1%v Ar, 5ppm He)
  - Gases that evolve from internal materials: ammonia (NH3), carbon dioxide (CO2), carbon monoxide (CO) are not uncommon by-products of internal curing of epoxies and adhesives
  - Gases that ingress through non-hermetic package: water, oxygen/argon from air, fluorocarbon from gross leak testing, He from fine leak testing. Will not see Kr85 because it is too small amounts
- What to look for:
  - Oxygen: Argon ratio of 20:1 indicates air – know if it is intentional (e.g. sealed in air) or unintentional ingress indicating a leak
  - Gas volume detected by IGA – this can be back-calculated from most machines on the market. If gas volume is not
    - Look out for parts that are evacuated (e.g. most oscillators)

Example of IGA results for one PN across multiple devices from different lots – what do you see?

SAMPLE ID	1	2	3	4	5	6	7	8	9
Pass/Fail	FAIL	PASS	PASS	FAIL	PASS	FAIL	FAIL	PASS	PASS
Inlet Pressure torr	48.3	42.5	41.4	38.7	37.2	37.4	26.9	29.7	29.1
Sys. Pressure torr	1.30E-05	1.20E-05	1.20E-05	1.00E-05	9.80E-06	1.00E-05	3.40E-05	4.10E-05	3.80E-05
Volume cc·atm	0.231	0.201	0.196	0.182	0.175	0.176	0.125	0.138	0.135
Nitrogen ppmv	785,813	996,301	997,499	975,279	981,917	982,119	975,867	986,468	986,429
Oxygen ppmv	187,669			3,513	821	981	13,064		
Argon ppmv	8,666	179	212	333	226	229	1,185	193	185
Carbon Dioxide ppmv	1,879	788	840	2,097	1,936	1,714	3,006	1,266	1,214
Moisture ppmv	15,758	763	767	5,406	4,551	5,344	5,119	710	541
Hydrogen ppmv	117	1,968	683	13,372	10,549	9,613	14	11,363	11,631
Methane ppmv									
Ammonia ppmv									
Helium ppmv							1,716		
Fluorocarbon ppmv	97						19		

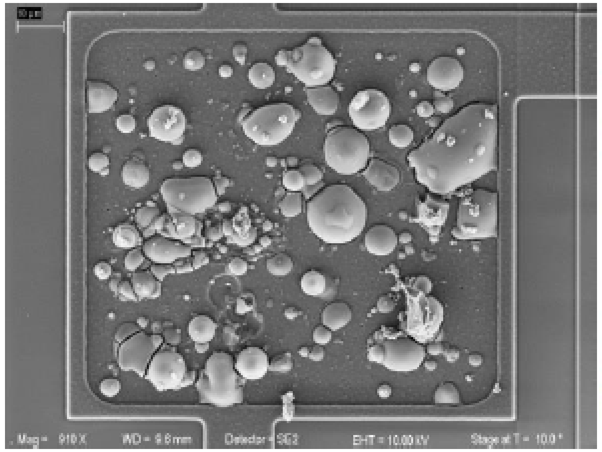
Corrosion inside microcircuit that lost hermeticity

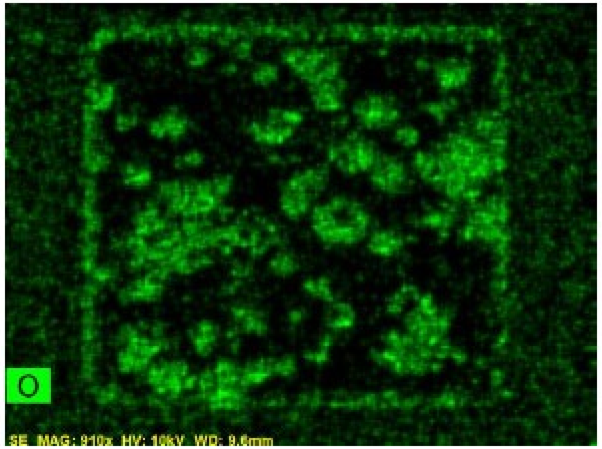
- Corrosion of aluminum pad in a cavity microcircuit due to moisture ingress and elevated temperature exposure during screening
- Native aluminum oxide soaking up water and releasing hydrogen to form a blister below the surface. Eventually the blister would fracture and aluminum hydroxide growth in columnar form (bayerite) would emerge
- The process is consuming aluminum from the pad. If the device had aluminum wires, they would have been consumed to the point of breaking

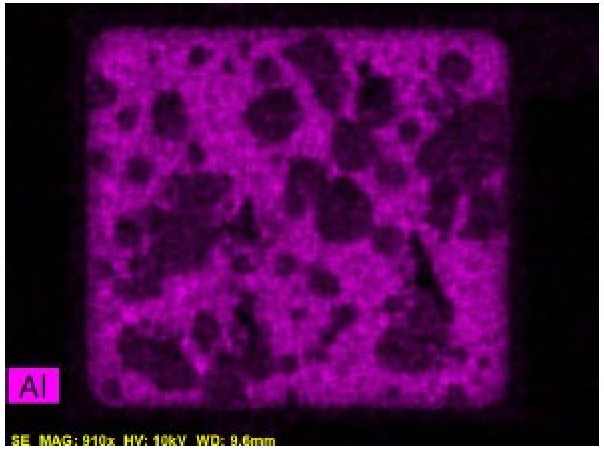


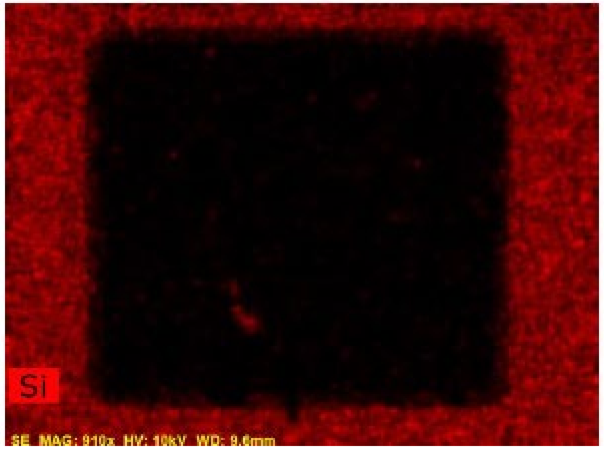
IGA results

Nitrogen	ppmv	351,074
Oxygen	ppmv	not detected
Argon	ppmv	228
CO2	ppmv	6,713
Moisture	ppmv	624,817
Hydrogen	ppmv	17,144
Methane	ppmv	not detected
Ammonia	ppmv	not detected
Helium	ppmv	not detected
Fluorocarbon	ppmv	24





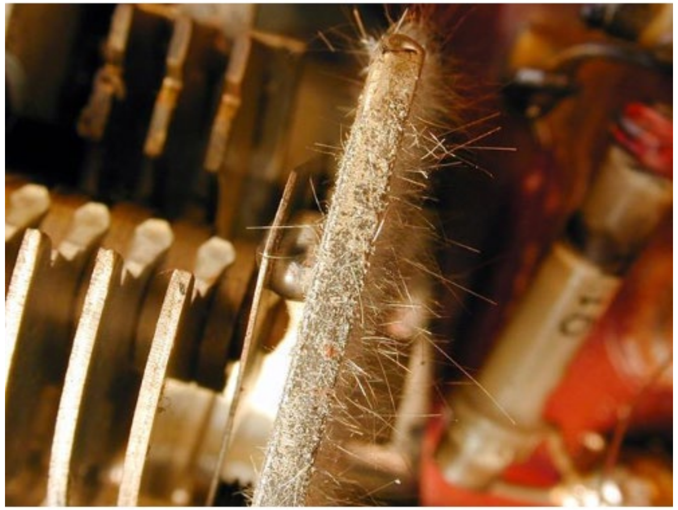




Metal Whiskers – what they are

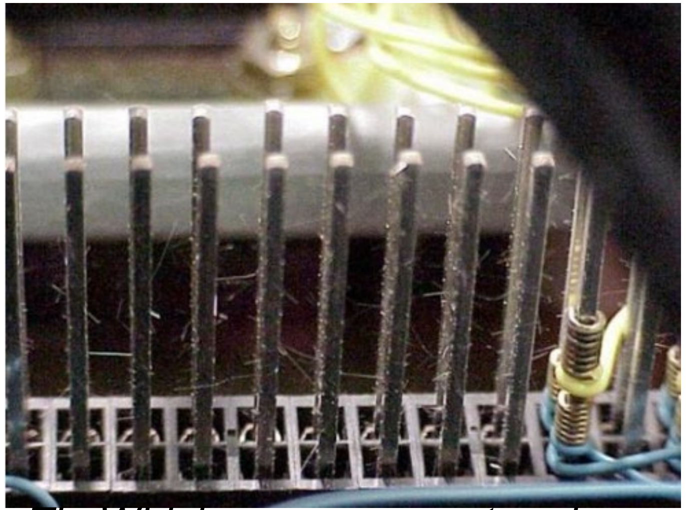
- Hair-like metal structures that erupt outward from a grain or several grains on a metal surface
  - May be straight, kinked, or odd-shaped eruptions

- Coatings of *Tin*, *Zinc* *and* *Cadmium* are especially able to develop whiskers; but, whiskers have been seen on Indium, Gold, Silver, Lead, and other metals too



Tin whiskers on tuning capacitor

Source Material	→	atoms from the metal itself
Transport Mechanism	→	primarily grain boundary diffusion
Transformation	→	diffusing atoms aggregate at the root (NOT the tip) of the forming whisker



Tin Whiskers on connector pins

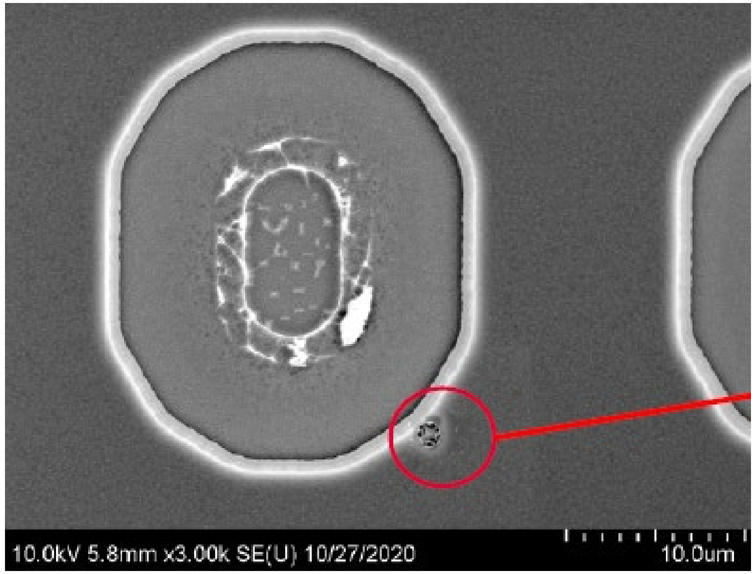
SAE-GEIA-STD-0005-2
Standard for Mitigating the Effects of Tin Whiskers in Aerospace, Defense, and High Performance Electronic Systems

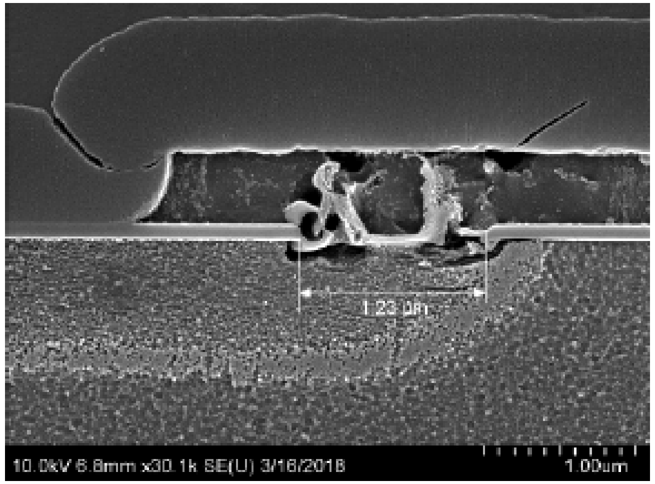
- An industry standard originally published in 2006, and updated in 2017. Currently undergoing another revision
- "This Standard addresses the risk of tin whiskers forming on Pb-free tin finishes. However, the state of research into tin whisker risk still does not allow accurate quantitative estimates of the risk and reliability. It defines three baseline Control Levels that detail the amount of attention that should be paid to the risk of tin whiskers: no restrictions on Pb-free tin finish use, some restrictions on Pb-free tin finish use, and prohibition of Pb-free tin finish use."
- Defines several control levels based on system criticality with suggested mitigations for different levels
  - From very low control levels that have no whisker mitigation to high control levels with prohibition of tin finishes
  - Most users likely fall in the middle, with some mitigations required
  - Mitigations include
    - Barriers, coatings, and potting materials
    - Circuit and Design Analysis
    - SnPb soldering process with validated coverage

Failure Mechanism: ESD and EOS

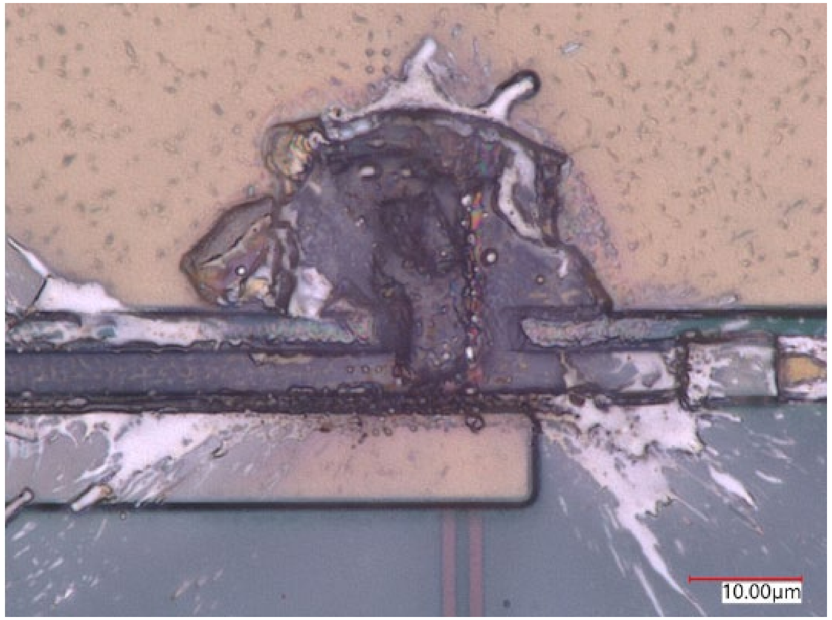
- Electrostatic Discharge (ESD) definition per ESD ADV1.0-2017 – the rapid, spontaneous transfer of electrostatic charge induced by a high electrostatic field. Note: Usually the charge flows through a spark between two bodies at different electrostatic potentials as they approach one another.
- Electrical Overstress (EOS) definition per ESD ADV1.0-2017 – The exposure of an item to a current or voltage beyond its maximum ratings. This exposure may or may not result in catastrophic failure
- During failure analysis
  - ESD is typically characterized by relatively small damage on the die, but this damage can be sufficient to cause electrical failure, or be a damage location that propagates to a much larger failure with continued use under rated conditions
  - EOS is typically characterized by relatively large damage on the die from Joule heating, melting or vaporizing of materials
- ESD can be considered a sub-type of EOS, or a distinction can be made based on the amount of damage seen to judge

ESD damage on surface and cross-sectioned





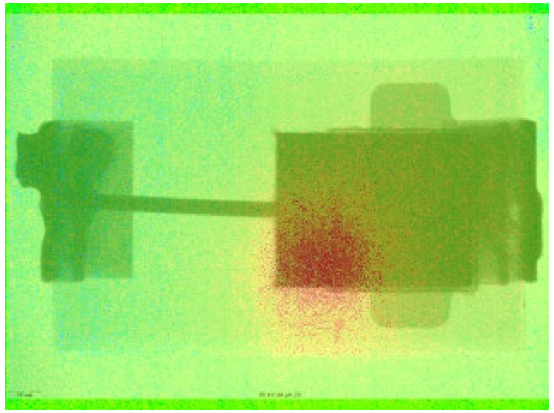
EOS damage

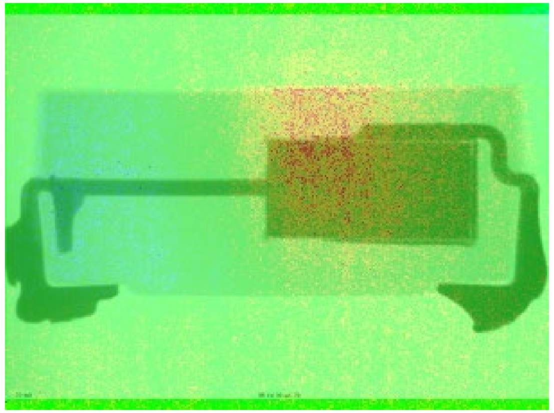


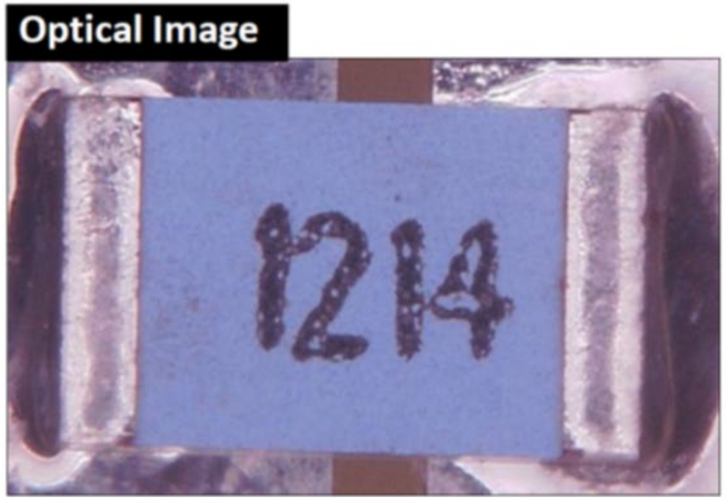
Infrared Inspection (IR)

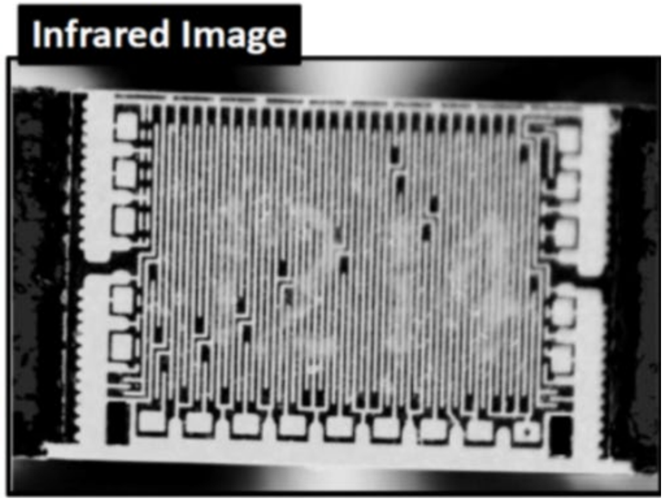
- Typically performed in the 3-12um wavelength to look for hot spots
  - Requires powering up the device
  - Requires a resistive short that generates enough heat to be detectable by the camera in use
- Can be useful to non-destructively examine through materials that are infrared-transparent
  - Si die – which makes infrared useful in back-side imaging, or in flipchip imaging
  - Passive devices with coatings

Overlay of X-Ray and Infrared imaging showing location of a short in a tantalum chip capacitor









Data Analysis and Visualization

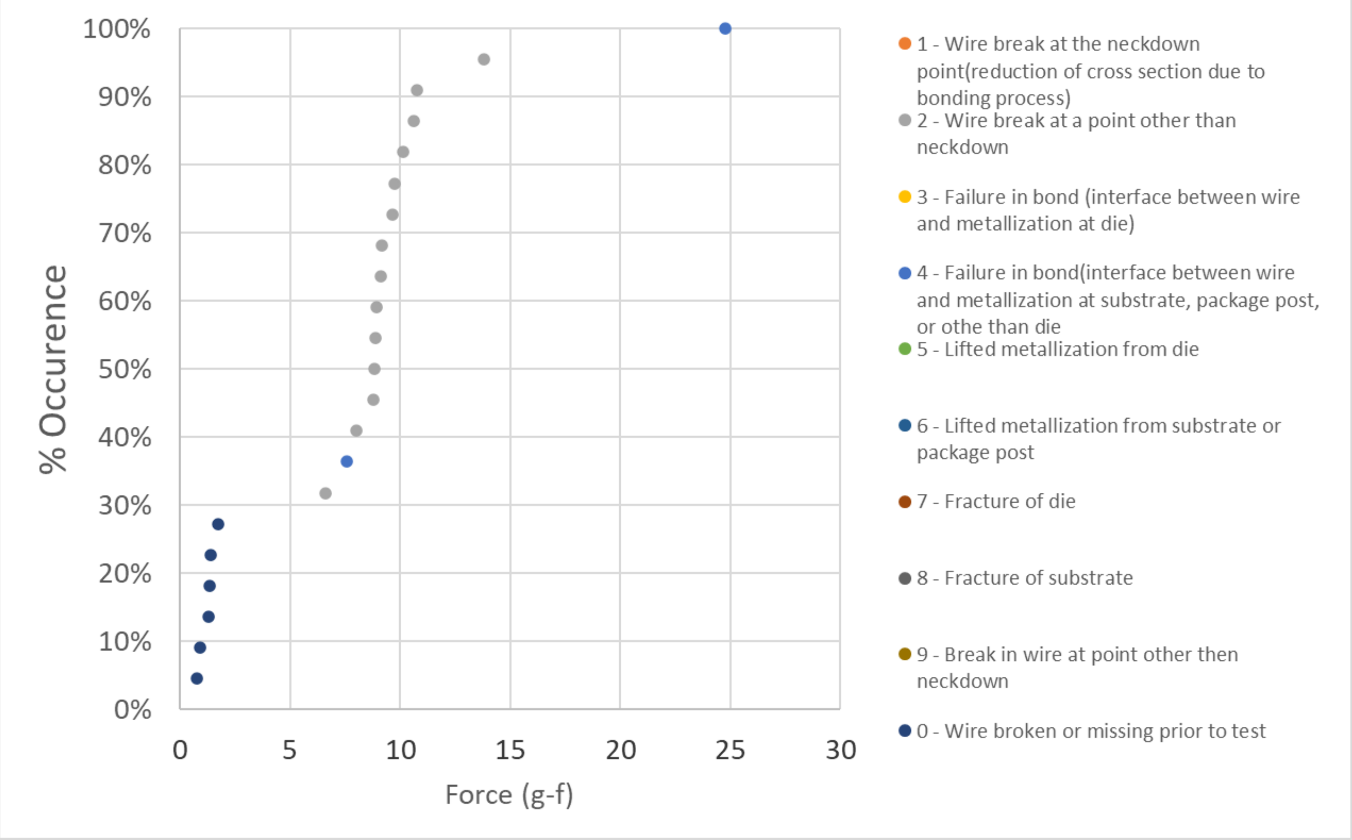
- Understand and simplify the data by gathering or developing tools to analyze and display the data
- Example: graphing wirebond pull data as cumulative distribution plot allows to see three sub-sets of data, with lower values all showing the same break code

From THIS

	Map No.	Force	Min. Accept Force
sn23 detector window	8	1.350 gf	2.500 gf
sn23 wire to detector	7	24.780 gf	2.500 gf
sn23 Header to post	1	10.600 gf	2.500 gf
sn23 post to dev lead	2	8.905 gf	2.500 gf
sn23 post to+Dev lead	3	7.985 gf	2.500 gf
sn23 lead to bottom o	6	1.730 gf	2.500 gf
sn23 FET lead to resi	4	7.560 gf	2.500 gf
sn23 resistor to post	5	9.100 gf	2.500 gf
sn14resistor to post	5	10.775 gf	2.500 gf
sb14 resistor to fet	4	9.755 gf	2.500 gf
sn14 resistor to det	6	1.300 gf	2.500 gf
sn14 fet+ to pos	3	9.665 gf	2.500 gf
sn14 fet- to pos	2	9.140 gf	2.500 gf
sn14 post to hea	1	13.795 gf	2.500 gf
sn14 det to supo	8	0.740 gf	2.500 gf
sn10 det to supo	8	0.900 gf	2.500 gf
sn10 fet to res	4	6.595 gf	2.500 gf
sn10 res to det	6	1.375 gf	2.500 gf
sn10 res to post	5	8.765 gf	2.500 gf
sn10 head to pos	1	8.860 gf	2.500 gf
sn10 post to fet	3	10.120 gf	2.500 gf
sn10 post to fet	2	8.835 gf	2.500 gf

Table 1: Wire pull results.

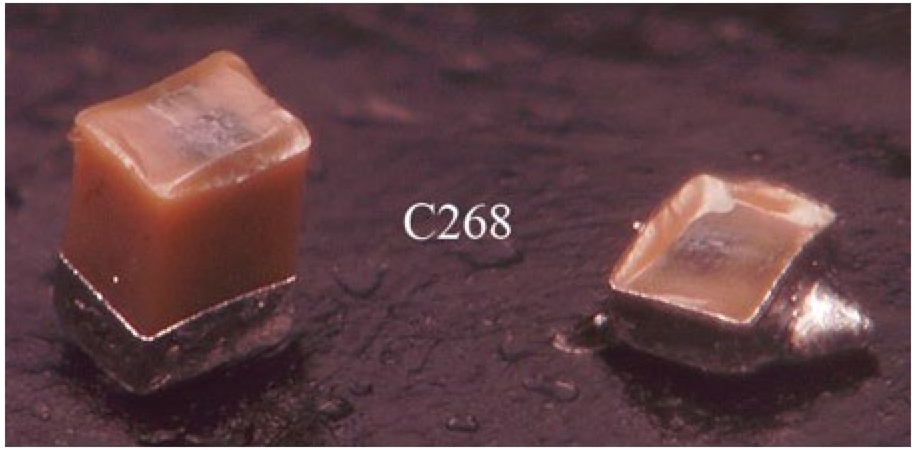
To THIS

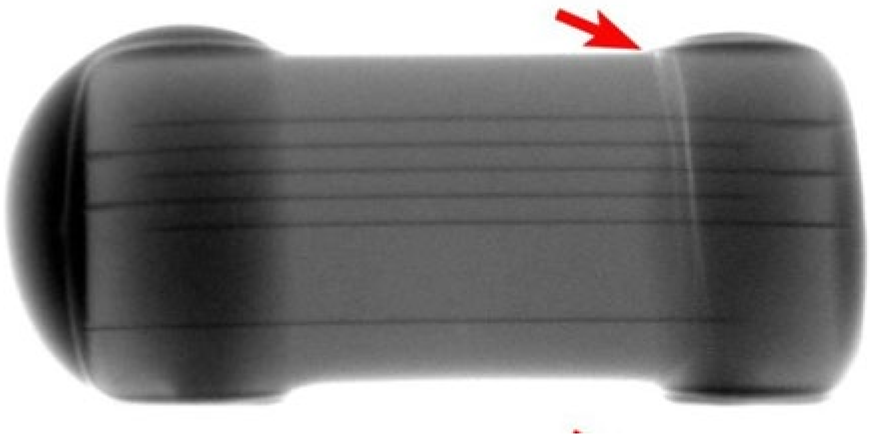


A gallery of failures

“The Front Fell Off”

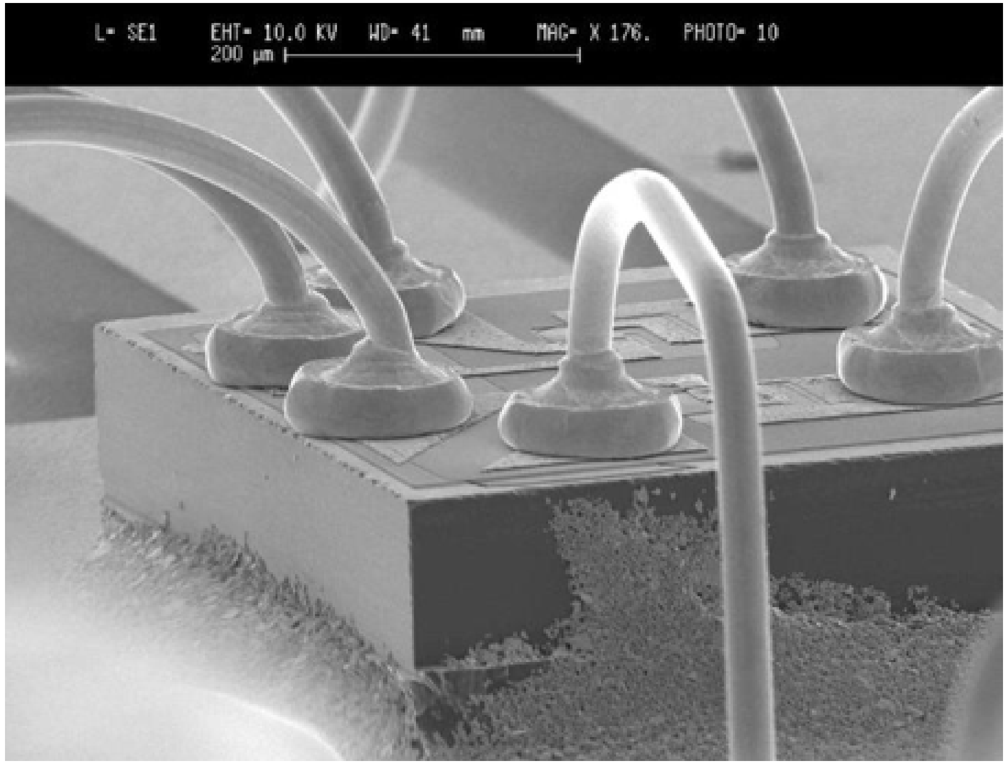
- Capacitors appear to have cracked during initial installation of the component on the board.
- Initial installation includes the original solder reflow and the probable hand solder touch-up.
- It is suspected that the touch-up process may have produced stresses (especially tensile stress) to the capacitor and that this resulted in the observed cracking beneath one end termination.
- Factors that may have contributed to the cracking failure of multiple capacitors include tensile forces applied to the capacitor by tools used to solder the components on the board

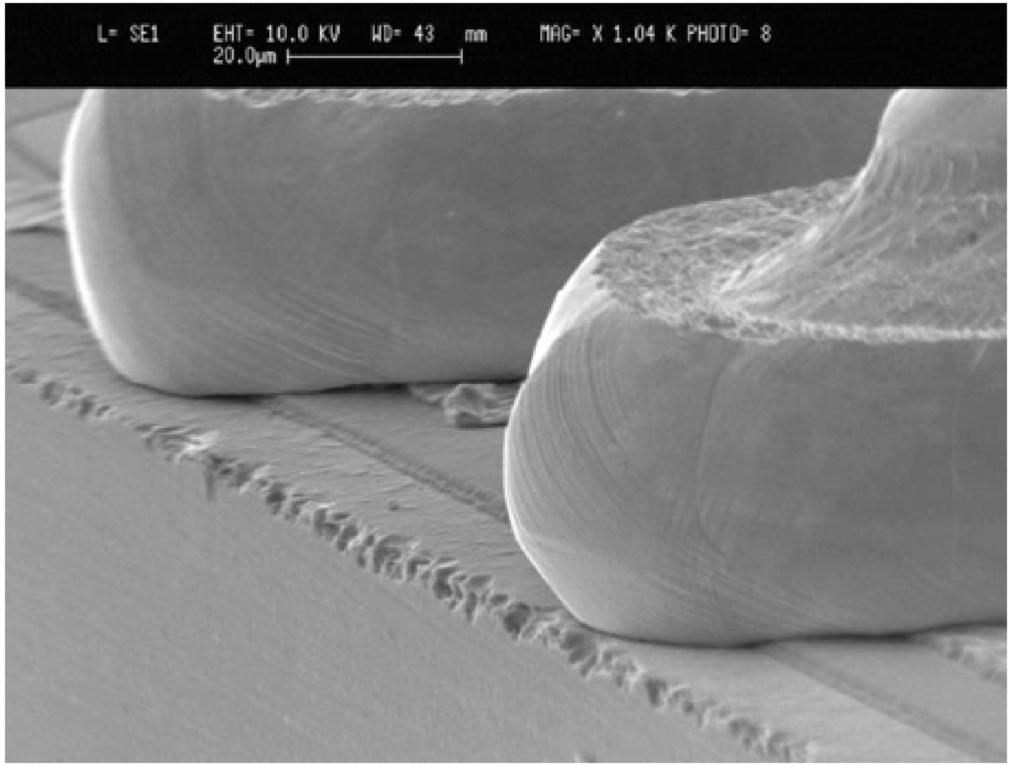




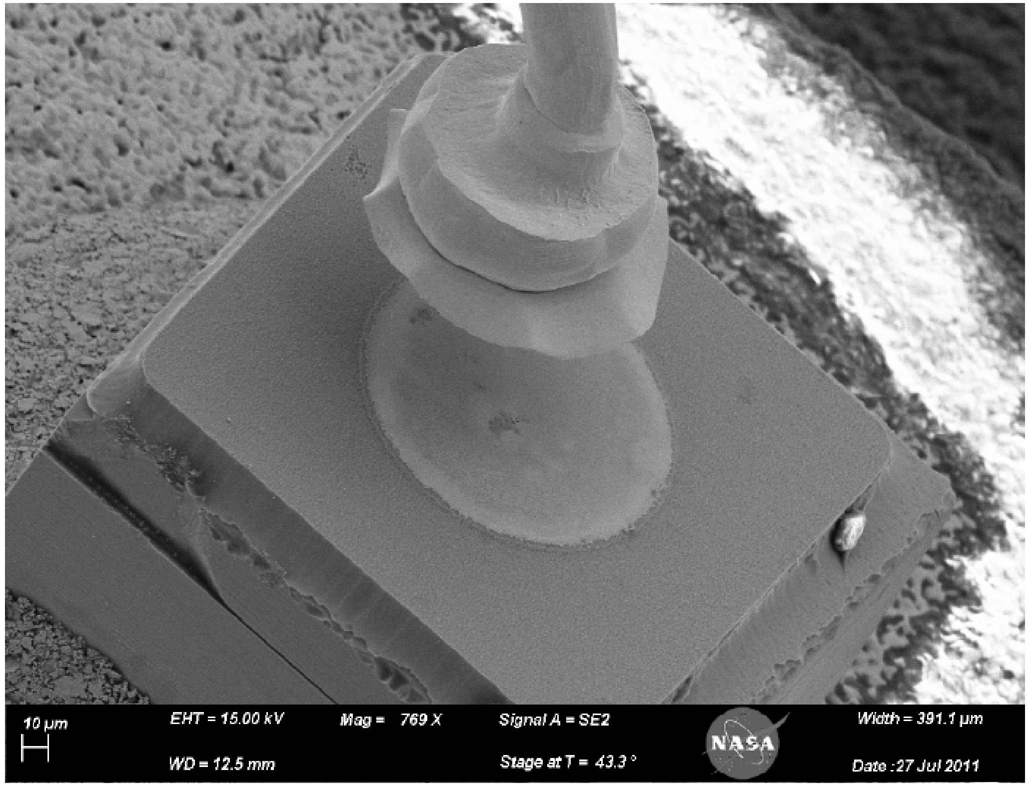
Clumsy Bond Placement

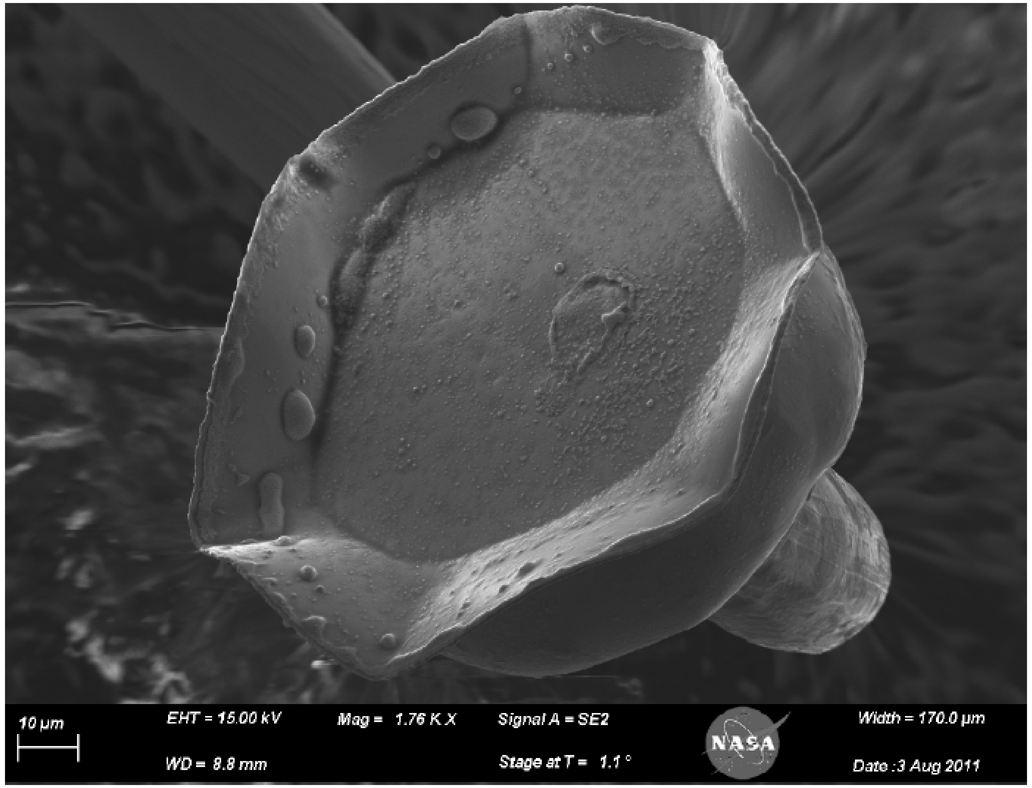
The cause of failure was a workmanship error that resulted in relatively large diameter ball bonds shorting to the unpassivated die edge of the transistor that drives the output stage of the hybrid. A thorough quality control inspection at the manufacturer should have revealed this workmanship defect. A pre-cap customer source inspection (CSI) also could be expected to reveal such a defect.





Lifting of die metallization pad

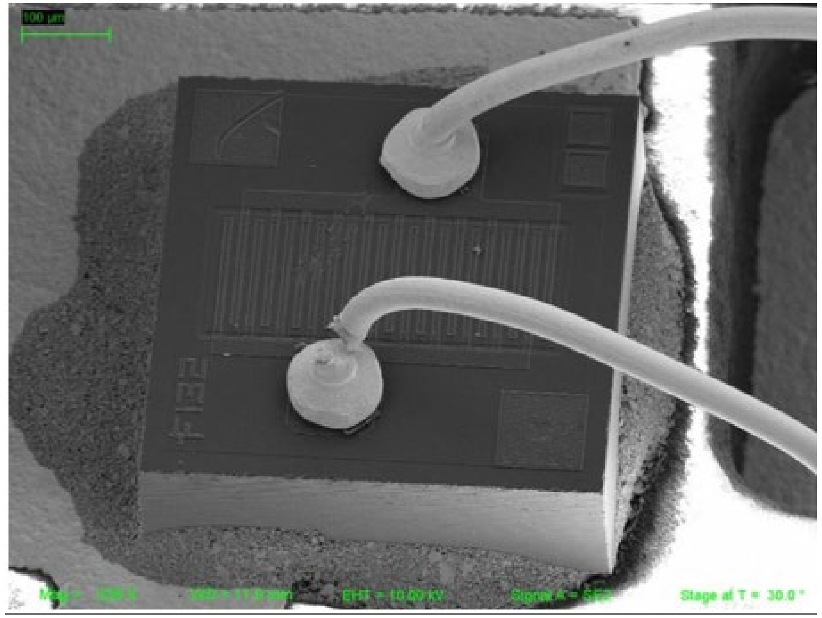


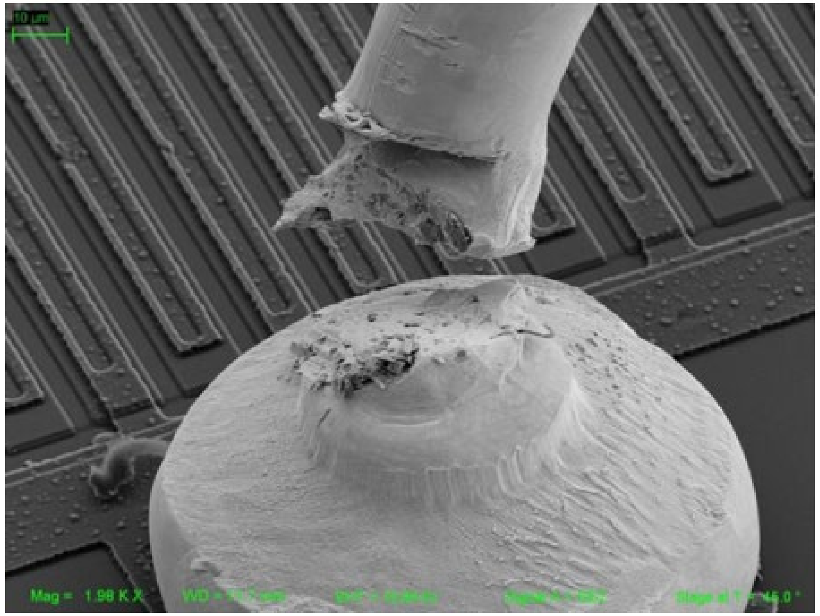


“The Guillotine”

- The device failure was caused by manufacturing-induced mechanical damage that severed an internal bond wire. The broken wire was visible in radiographic examination prior to delidding the device. It was difficult to see optically during internal examination. Nonetheless, scratch damage on the die surface should have been seen by a pre-cap inspection. It is questionable if this device functioned properly during manufacturer testing.

  The broken wire connects to a JFET that is used to turn off the output MOSFETs. With the JFET removed from the circuit (due to the broken wire), the MOSFETs were slow to turn off since charge on the gate (capacitance) had to be discharged through the phototransistors.

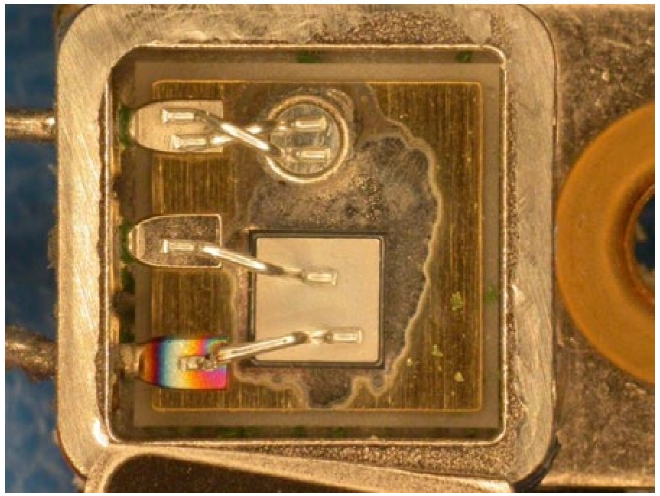


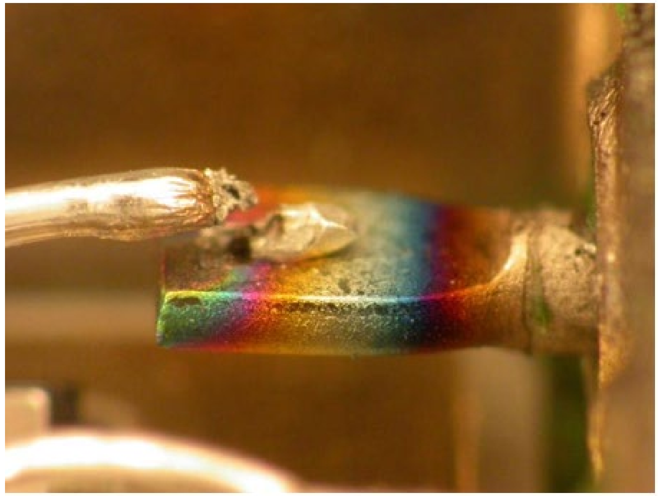


"Somewhere Over the Rainbow"

- External mechanical stress caused catastrophic damage to the lead glass seal that allowed movement of the lead and resulted in the propagation of a crack at the heel of the wire bond at the lead paddle inside the device. As the crack grew, the current path traversed a decreasing cross-sectional area of wire with an increasing electrical resistance and corresponding joule heating. The heating was such that the aluminum wire became liquid in the vicinity of the crack along the length of wire leading to the die. Residual bending stress caused the wire to spring up, disconnecting the wire. The final assault was arcing and vaporization of the last remnant of aluminum filament connecting the lead and wire.

  Workmanship and quality control are partially to blame for this failure. However, the ultimate cause of this failure was the assembly design that did not anticipate the tremendous mechanical stress that could be imposed on the delicate glass feed-through seals of this device.





Attributes of a Good Failure Analyst

- Knowledgeable about EEEE parts they are analyzing
  - Understanding manufacturing, assembly, storage, testing
- Knowledgeable about EEEE part use application
- Knowledgeable in tools and techniques of failure analysis
  - Perform work accurately and document the steps to avoid finger-pointing in the future
  - This includes also knowing when to seek help
- Good communicator
  - Ask the engineering team about additional background information
  - Able to write and talk accurately and concisely to explain the analysis to the customer
  - Respectfully disagree, as needed
- **Curious for life**
  - Knowing where to look for reliable information (e.g. published papers, industry sources, application textbooks)
  - No one is born with this knowledge - continuous education is important, both structured and self-education

Thank you

- This presentation was only possible with the support of the NASA GSFC parts analysis lab, whose analysis and conclusions were presented throughout
- Jay Brusse (SSAI at NASA GSFC), for the review and materials

Questions?