COURSE NOTES

GREEN
TJ GREEN ASSOCIATES, INC

Microelectronic Packaging Failure Modes and Analysis

Virtual Training (2 Sessions)
January 28-29, 2021

Instructors: Tom Green, TJ Green Associates, LLC, tgreen@tjgreenllc.com
Bob Lowry, Electronic Materials Consultant, Rlowry98@aol.com

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Opening Remarks

- Welcome
- Logistics
- Instructor's Background
- Session being recorded

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Scope

- Review and highlight the typical kinds of microelectronic packaging related failures that occur during manufacturing, qualification and the unfortunate field failures, and present the FA tools and techniques that are utilized to understand root cause and guide corrective actions.
- Ask questions anytime

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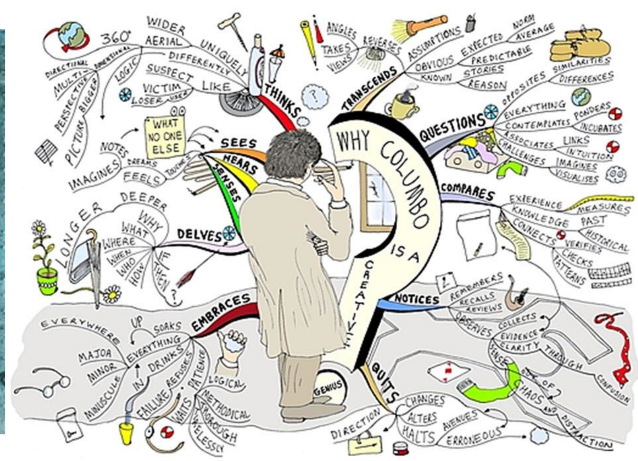
Microelectronic Forensics

- Just like CSI but no crooks … Except for Counterfeit parts.
- Sherlock Holmes / Columbo



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COURSE NOTES

Course Outline

- Introduction Terminology and Product Definitions
- Failure Analysis (FA) Process Flow and overview
- Typical Package Related Defects and Failures (today)
- Failure Analysis Tools and Techniques

REVIEW COURSE OUTLINE

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DoD FFRP Process Flow

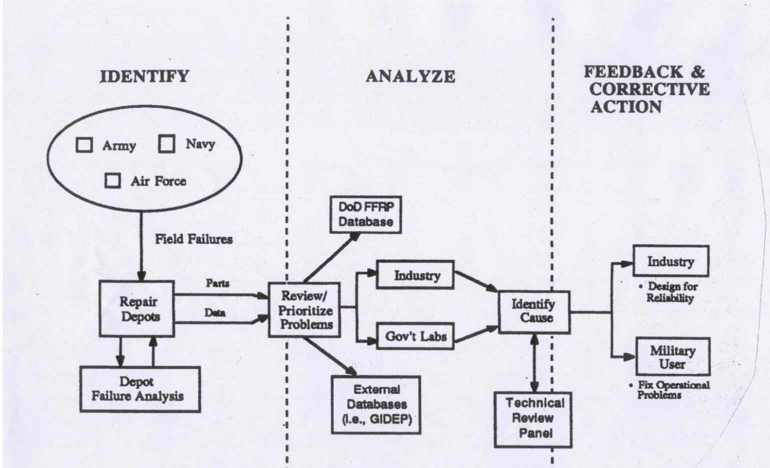

FIGURE 1.1-1: FFRP PROCESS OVERVIEW

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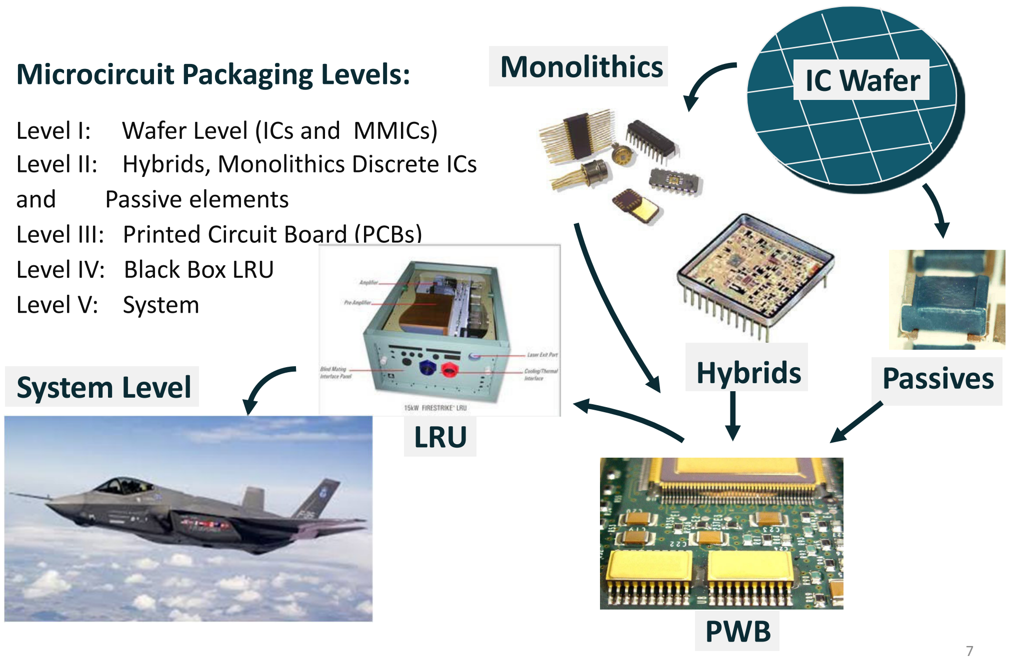
COURSE NOTES

Electronics' Packaging Hierarchy

Microcircuit Packaging Levels:

Level I: Wafer Level (ICs and MMICs)
Level II: Hybrids, Monolithics Discrete ICs and Passive elements
Level III: Printed Circuit Board (PCBs)
Level IV: Black Box LRU
Level V: System



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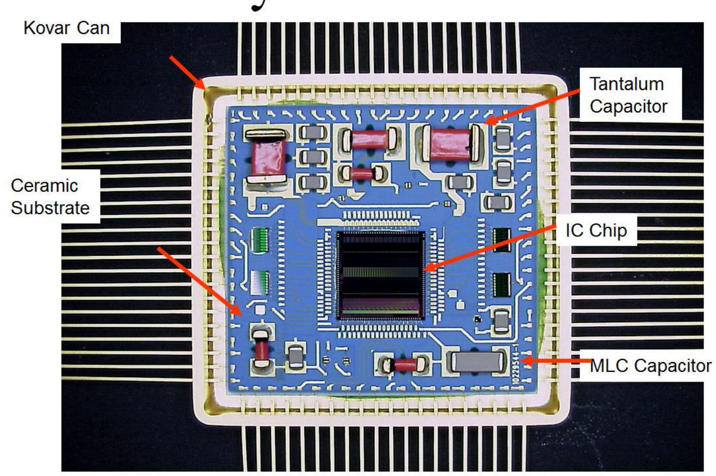
Hybrid Circuit



- DEFINITION . . .

  Single or multiple layers of conductors, resistors and/or capacitors deposited on an insulating substrate…Discrete semiconductors, IC's, capacitors, resistors and/or inductors are mechanically connected to the deposited conductors.

 Ref: NASA JPL 5

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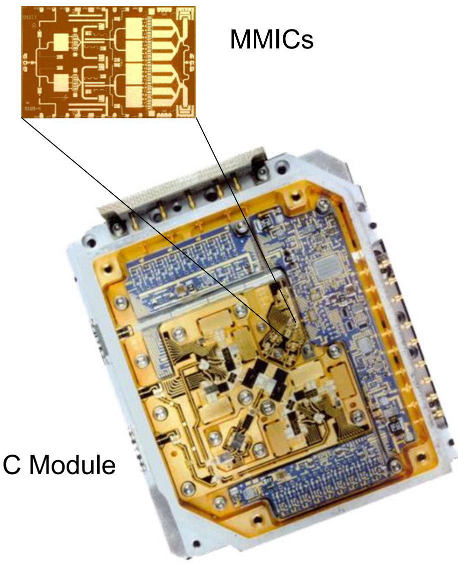
RF MMIC Modules (Monolithic Microwave Integrated Circuit)

RF MMICs also known as microwave hybrids or "MIC" hybrids are very similar to conventional Hybrids in many ways, but operate at much higher frequencies and make use of gallium arsenide (GaAs) technology.



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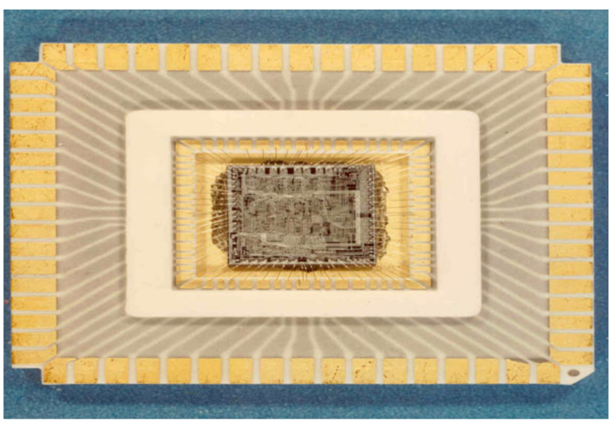
Monolithic Integrated Circuit

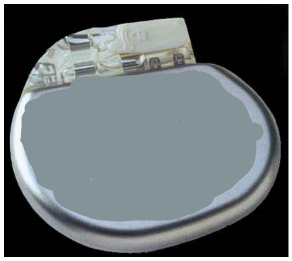
(Single IC Chip in 32 Pin CERDIP)



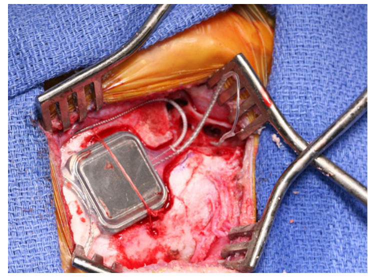
- DEFINITION . . .

  A.3.1.3.4.3 Monolithic microcircuit (or integrated circuit). A microcircuit consisting exclusively of elements formed in situ on or within a single semiconductor substrate with at least one of the elements formed within the substrate.

Class III Medical Implants



Pacemakers



Cochlear Implants

Neurostimulators

HERMETIC DEVICES

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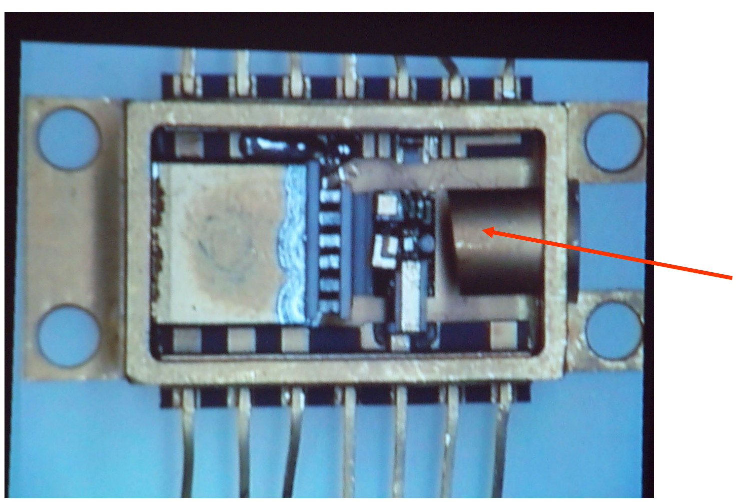
OPTOELECTRONICS
View Inside a Pump Laser



Ball Lens

Telecomunication Industry devices are Hermetic Ref: Telcordia GR 468 Core

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Introduction

A failure analysis is a systematic investigation of failed electrical and mechanical components to determine root cause of failure and guide corrective actions. A series of non-destructive and destructive tests and evaluations are conducted to confirm the failure mode. Product design or process changes often result from the FA investigation.

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Component Failures

- Failures can occur during:
  - Initial design and qualification phase
  - During 100 % Screen Testing
  - Field Failures ☹
- It's critical to reproduce the failure and determine root cause which drive corrective actions:
  - Design change
  - Material and/or process change
  - Modification of the product/customer specification
  - Add, delete or modify environmental testing

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Failure Analysis

- The purpose of FA is to:
  - Verify that a failure exists
  - Understand the symptom (failure mode)
  - Determine the failure cause (mechanism)
  - Suggest and guide corrective actions
- The goal is to determine root cause

Caution is required to avoid losing or destroying data.

  - The analysis starts with non-destructive examination and measurement and proceeds through disassembly and destructive analysis.

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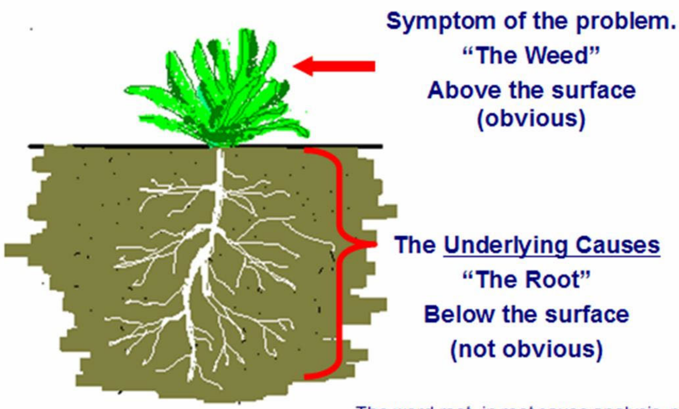
Root Cause

Root Cause Analysis Basics



The word root, in root cause analysis, refers to the underlying causes, not the one cause.

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Failure Analysis Techniques

- Failure Analysis Techniques
  - Non-destructive e.g. SAM (Scanning Acoustic Microscopy)
  - Destructive e.g. cross sections
  - Potentially Destructive e.g. X-ray radiography may erase data in an EEPROM

Be sure to do any relevant Non-Destruct analysis/testing first
How many failed parts are there?
Which ones to test and which ones to save.

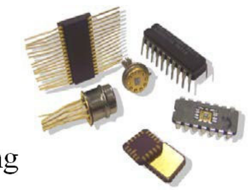
FA Process Flow

- Flow Chart
- Collect information about failure
- Electrical verification, curve tracer
- Non-destructive analysis and testing
- Destructive analysis and testing
- Identify root cause if possible
- Write report
- Assist in corrective actions and customer follow up

Always document “as received” condition

FA Example

Steps include (semiconductor example):



- External visual examination
- Electrical characterization to verify failure
- Curve tracer, circuit simulation, temperature testing
- Hermetic seal
- Particle Impact Noise Detection
- X-ray
- Residual Gas Analysis (if warranted)
- Open and internal examination
- Next steps vary widely depending on what is found –Localization of failure site, deprocessing, chemical analysis, overstress simulation, microprobing, etc.

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FA Methods for Hermetic Packages

- External Visual Inspection... to assess overall exterior quality/ workmanship.
- Real Time X-Ray Inspection... to nondestructively detect internal defects.
- Particle Impact Noise Detection... to detect loose particles inside cavity.
- Hermeticity and Internal Vapor Analysis... to quantify package integrity and internal atmosphere. These test methods may be used to gauge the susceptibility of a device to moisture-related failures triggered by poor sealing processes or internal post-seal outgassing.

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FA Methods – Plastic Encapsulated Components

- External Visual Inspection … to assess overall exterior quality/workmanship
- Real Time X-Ray Inspection and/or Scanning Acoustic Microscopy Inspection … to non-destructively detect internal defects.
- Decapsulation … chemically or physically remove encapsulant to expose the component for additional analysis.
  - Use caution not to etch away the evidence!
- Internal Visual Inspection, Optical Microscopy … optically examine die or other active components for physical defects.
- Internal Visual Inspection, Scanning Electron Microscopy … SEM examination of die or other active components at higher magnification for physical defects.

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Typical Micro Failure Modes

- Die and substrate cracking
  - Review X-Ray and Acoustic
- Wire and ribbon bond failures
  - Wire lifts, cracks and intermetallics
  - Cross sections
- Plating issues
  - Cause problems at die bond wirebond and package seal
- Gold embrittlement of solder joints
- Loose conductive particles…importance of PIND test
- Moisture related failures… corrosion
  - Review of hermeticity testing and RGA as an FA tool
- EOS/ESD type of failures
- Plastic Package Failure Modes

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FEA (Finite Element Analysis)

- ✓ When thermomechanical stress exceeds the strength of the material the result is failure!

Stress > Strength = Failure

- ✓ FEA is a 3D numerical solution for calculating stress and strain, sections the component into a finite number of elements and assume a linear function in between
- ✓ FEA can be used to predict stress on the elements due to thermal excursions that result from internal (power on/off) or external temp extremes (thermal vac..T/C cycle, burn in ect)
- ✓ Also used to predict and model external stress such as Pyro shock, random sinusoidal vibration experienced during launch an operation

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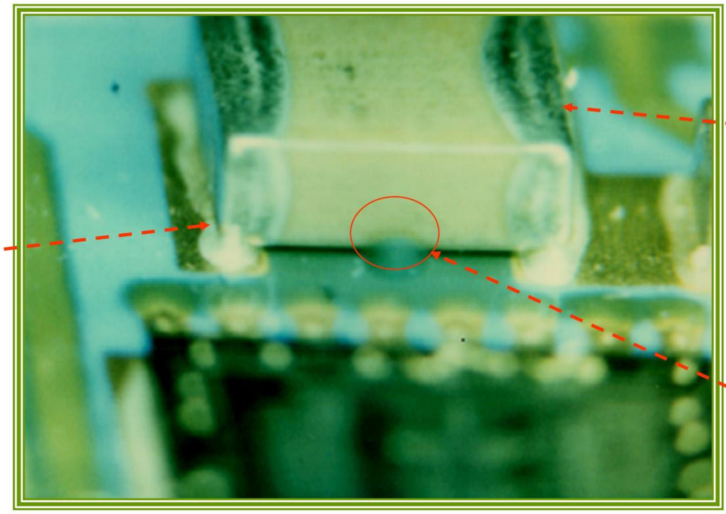
Stake Bonded Chip Capacitor

ACCEPT



NOTES: Acceptable…Photo shows a large ceramic chip capacitor with non-conductive staking compound added to the body of the component to add strength and prevent a failure during centrifuge testing. Conductive silver epoxy is used on the end terminations. (12X)

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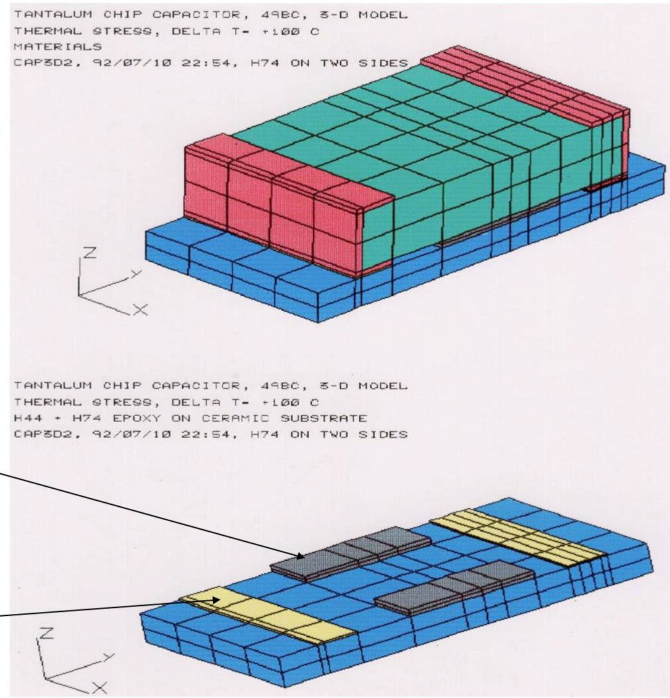
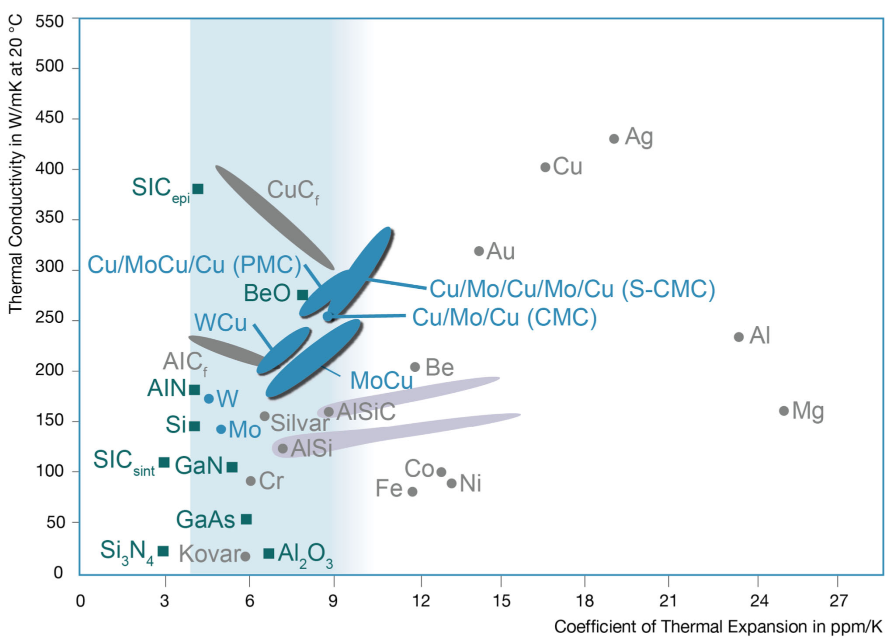
FEA Model



H74 Con-conductive Epoxy

H44 Conductive Ag Epoxy

Thermal Conductivity vs CTE



Ref: Plansee

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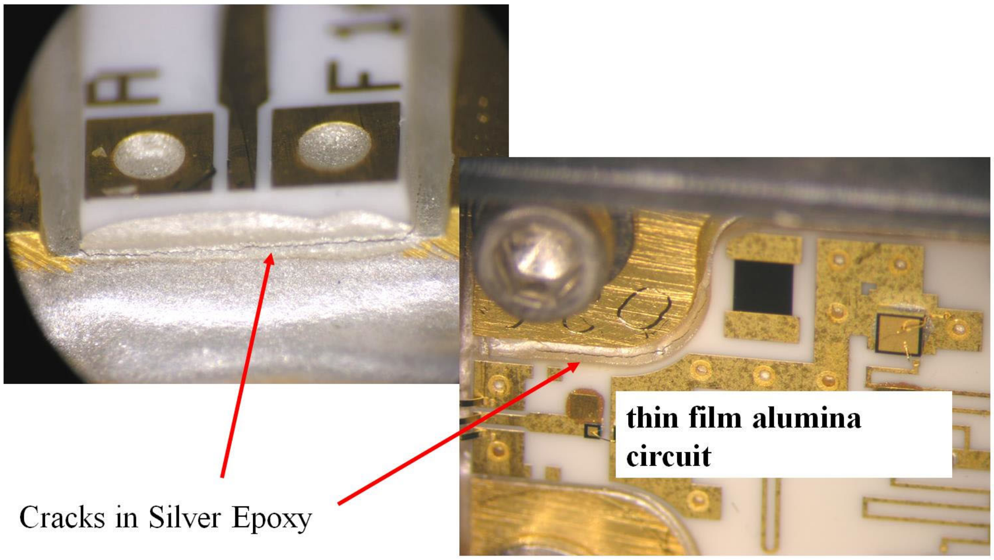
Epoxy Cracks in Fillet



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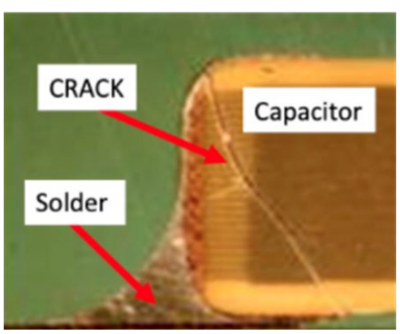
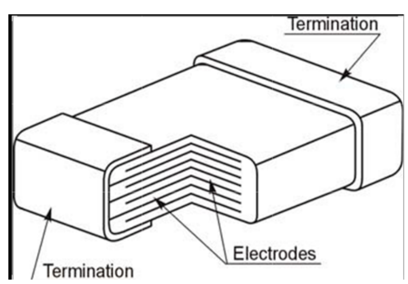
Capacitor Cracks





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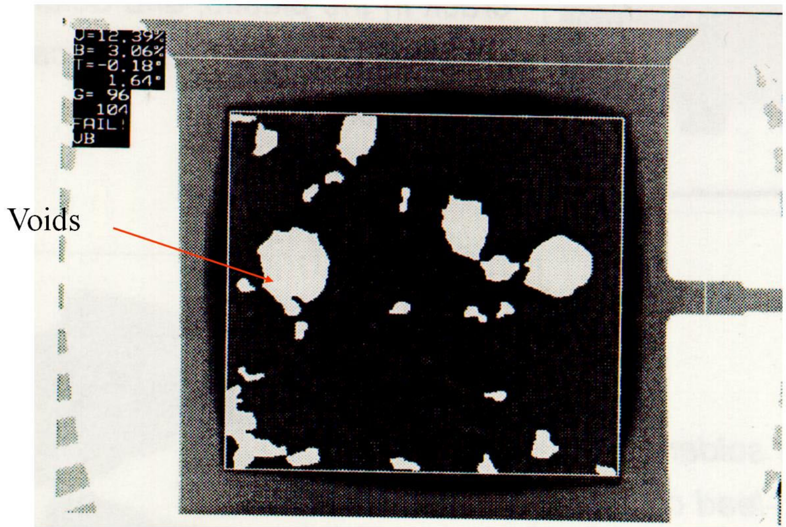
X-Ray of GaAs Die Attach



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Latest in X-Ray..Microfocus Imaging

- *Conventional X-ray testing creates a shadowgraph image on a piece of film, which limits resolution and can be difficult to enlarge*
- *Microfocus radioscopy provides an alternate high resolution image using a smaller X-ray source and Computed Tomography (cross sectional images and real time scan, % voiding die attach calculation and X-Y image resolution below 1 micron…supposedly)*

Ref: www. Feinfocus.com

https://www.nordson.com/en/divisions/dage/x-ray-inspection

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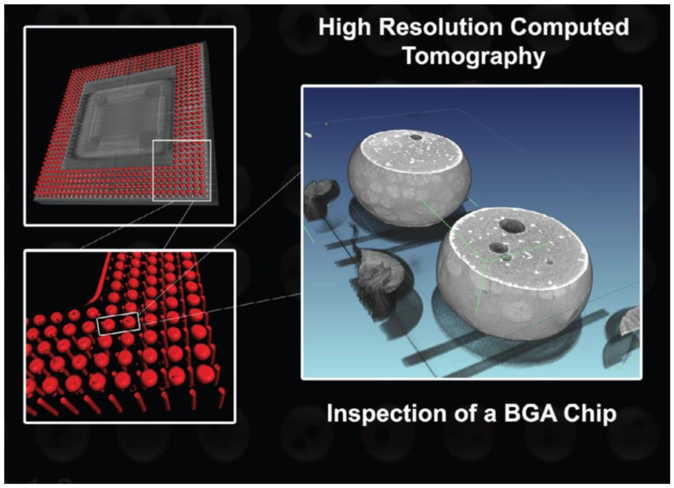
Computer Tomography…aka 3D Xrays



High Res Video: http://xviewct.com/industrial-ct-video/bga-chip-video

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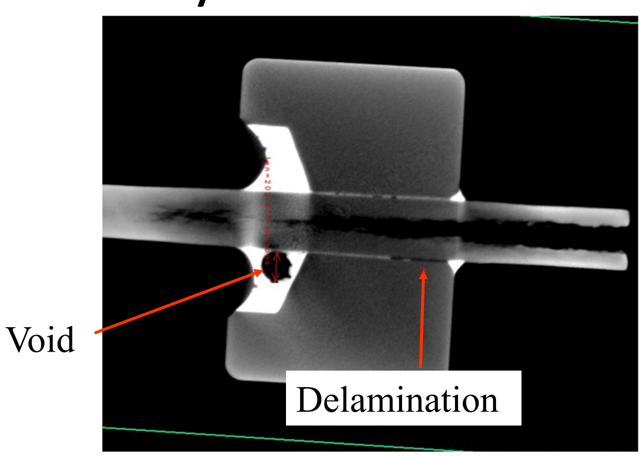
CT X-Ray of Voids in Feedthrus



CT X-Ray scan showing a cross-section of an axial device and the locations of the voids. Also shows delamination between the pin and the feedthru material.

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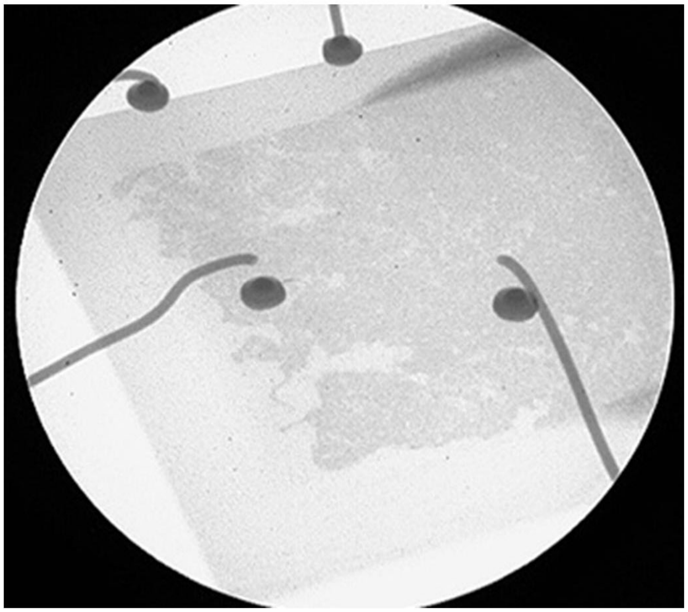
Wirebond Defects Seen by X-Ray



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X-Ray Principles

- All X-ray techniques depend on variation in material density to form the image and show sufficient contrast to highlight defects
- X-Ray is good for finding voids in die attach and lid seal and for spotting loose material in cavity
- OK for Ag filled epoxy not so good for polymer die attach
- Issues with resolution and contrast in hybrids with ceramic substrates and high density heat spreaders CuW
- Good at finding voids (e.g. in lid seal, glass, die attach) and cracks …not so good at detecting delaminations

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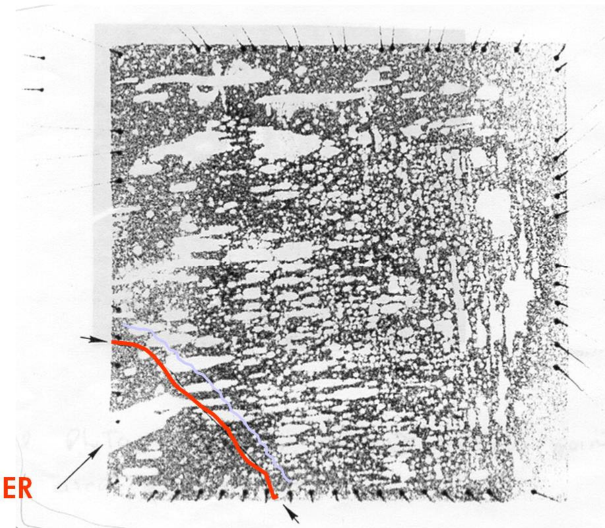
Conventional X-Ray of Die Attach (Au-Si)



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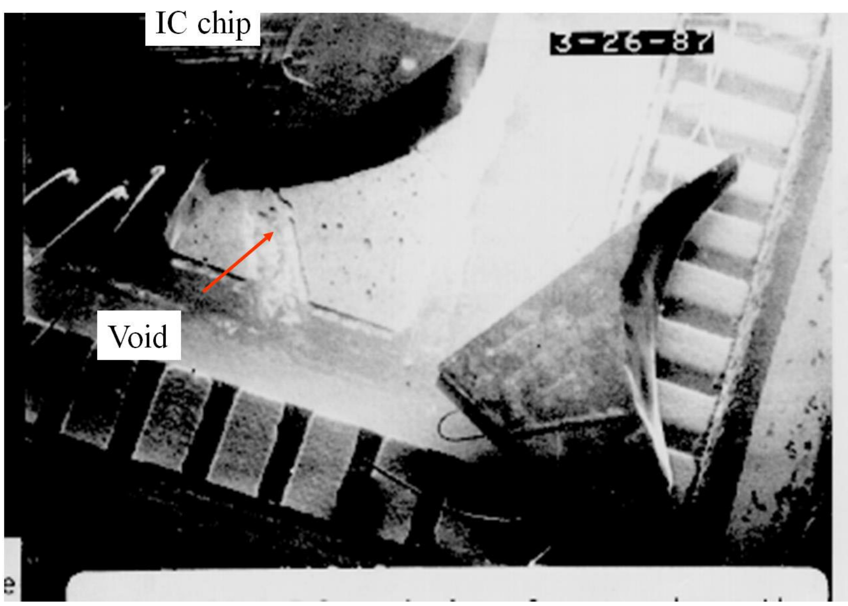
Die Bond Failure in F-16 Fighter



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Radiography TM 2012

- Non-destructive examination looking for voids in die attach, sealing defects, foreign objects, loose or misplaced wires, solder balls etc.
- Not all materials can be X rayed
- Ref 883 general requirements for viewing angles
- Reject for:
  - Presence of extraneous matter, allowed to PIND test then re compare
  - Unacceptable Construction: die attach voids, defective seals (a reject is when the seal width is reduced by more than 75%), inadequate wire clearance etc..

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SCANNING ACOUSTIC MICROSCOPY

- **Focuses sound waves to image samples.**
- **For sound wave transmission sample must be immersed in a coupling liquid, most often water or isopropyl alcohol.**
- **Very effectively used for locating discontinuity-type defects in assembled components such as voids, interfacial delaminations, cracks, etc.**
- **Can be used in a number of different “modes” depending on sample condition and information needed.**

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Acoustic Micro Imaging

- The sample is injected with ultrasonic sound waves and through careful analysis of reflected waves voids, delaminations and material discontinuities are imaged and highlighted.
  - Used on a variety of devices including chip capacitors and plastic components such as BGAs and QFPs
- The ultrasonic wave interacts with the sample and is absorbed, scattered or reflected whenever there is a change in material properties.
  - Material discontinuities show up as color differences on the viewing screen
  - Devices are usually immersed water or some other inert fluid
- Use with caution…high degree of operator skill required and images are easy to misinterpret

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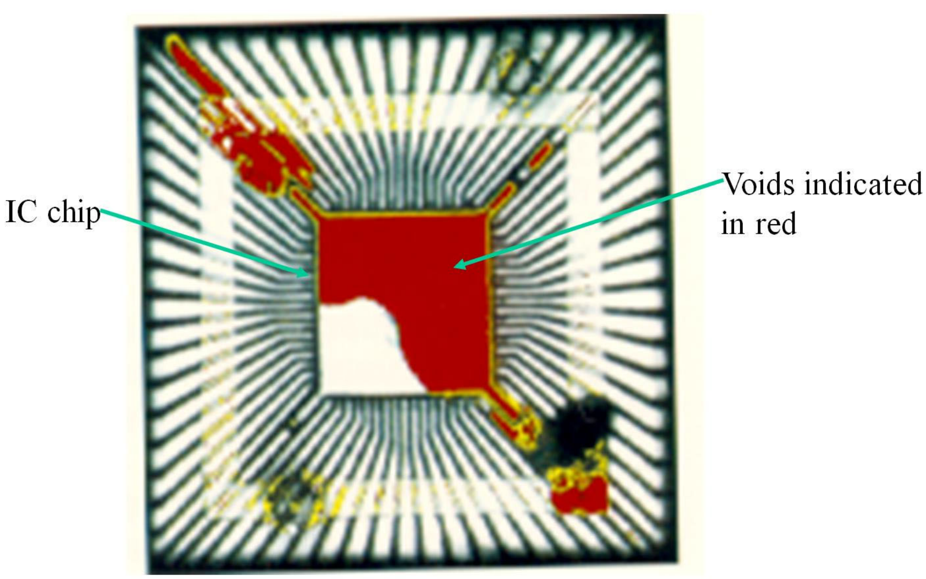
Acoustic Microscopy... Voiding



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Wirebond Related failures

- Wirebond Bond lifts
- Cracks at heel or neck
- Overbonding causing cracks and damage to IC
- Excessive Intermetallic growth i.e. “Purple Plague”
- Cratering of the MMIC or IC

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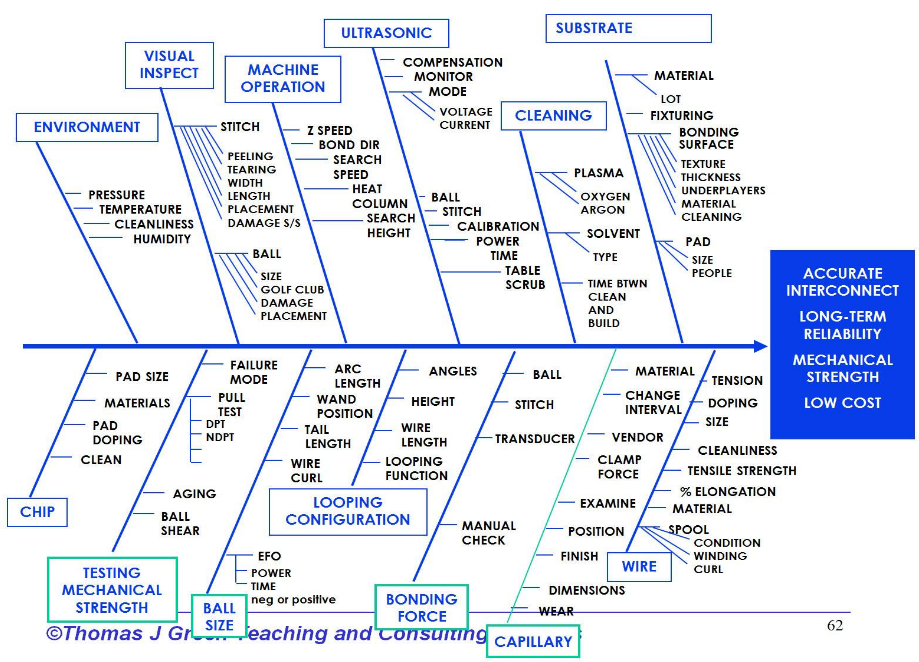
WIREBONDING CAUSE AND EFFECT DIAGRAM



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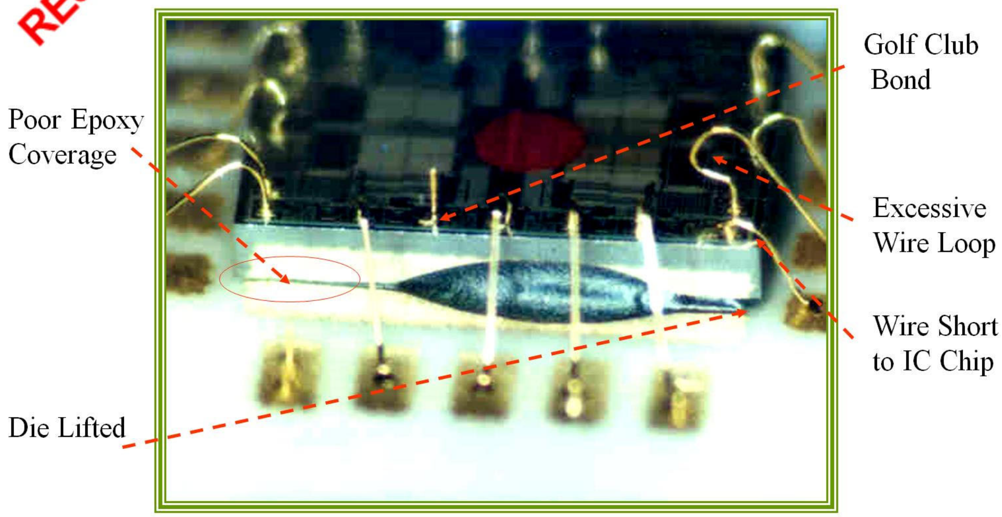
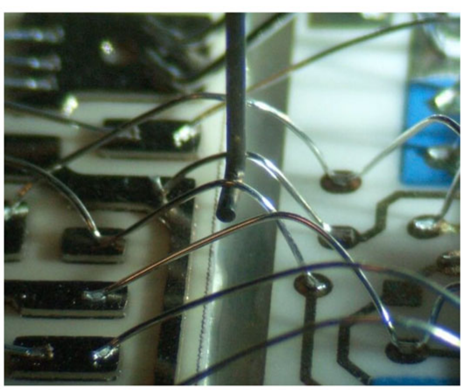
REJECT

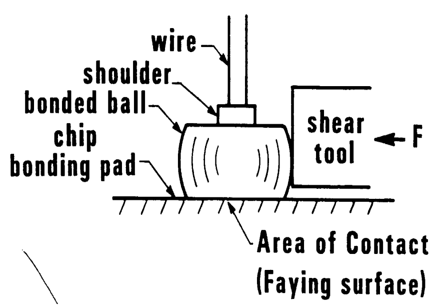
IC Assembly Multiple Defects



NOTES: Reject...Photo showing multiple assembly related defects. (50X)

Wire Pull Test Ball Shear





Destruct and Non-Destruct

Destruct Only

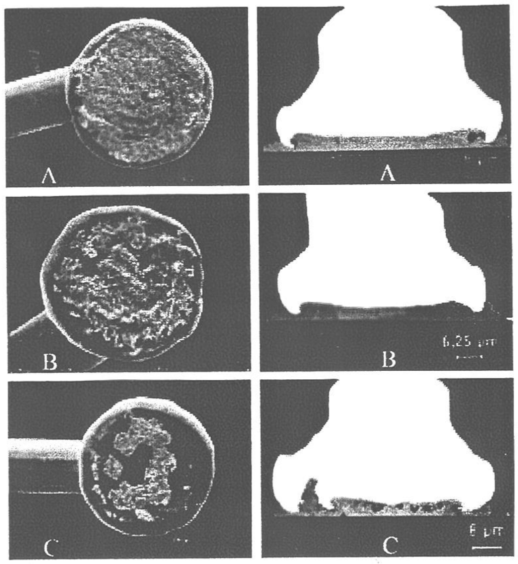


Fig 4: Left: IP coverage of different bond quality levels after bonding.
Right: Cross-sections after 500hrs storage at 175°C

Etching away of bond pad metal can reveal voiding underneath the ball

Table 1: Example of achieved shear strength and coverage for target conditions.

Bonding condition	Shear Strength	% coverage	Ref. to fig. 4
High strength	6.5	~77%	A
Nominal	5.5	~63%	B
Low strength	4.5	~34%	C

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Bottom Side of Au Ball Bond

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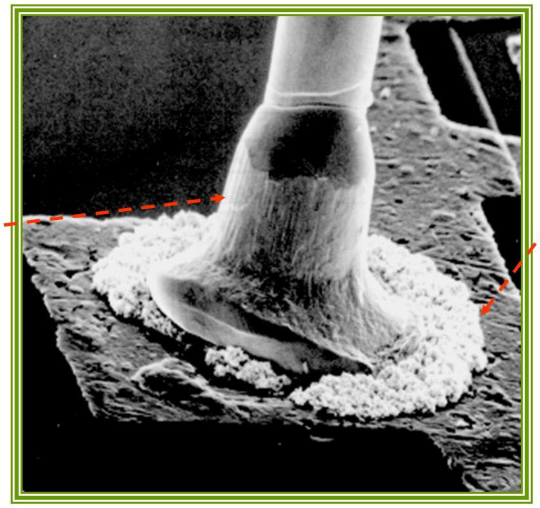
Purple Plague

REJECT

Grossly deformed ball bond



Au/Al Intermettalic Growth

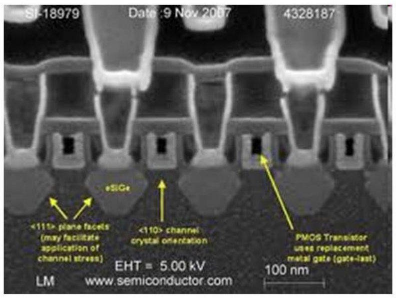
NOTES: Reject .. SEM photo shows evidence of an intermetallic formation around the bond perimeter. Through an optical microscope the growth will appear white and fluffy. Indicates a potential for a long term reliability problem.

Ref: Harmon[4]

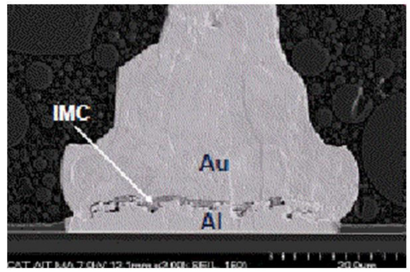
Intermetallic Compounds Au-Al

Compounds	Appearance
Au Al2	Purple
Au Al	White
Au4 Al	Tan
Au5 Al2	Tan
Au2 Al	Tan

Metallurgical Cross Sections

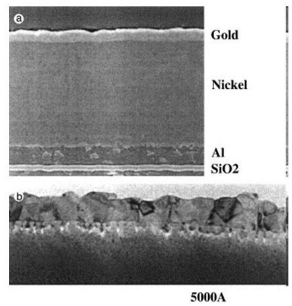


IC level



Ball Bond

Electroplating



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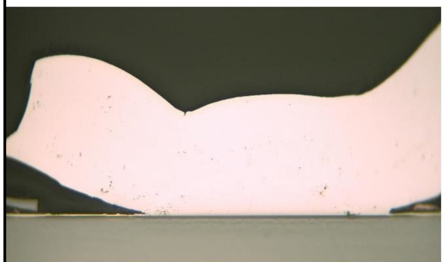
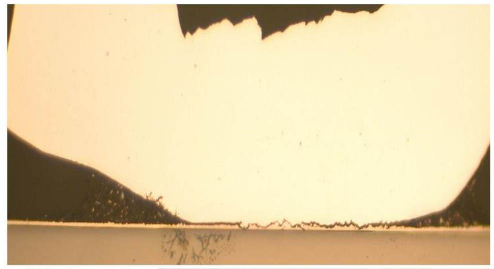
Cross Sectioning is an Art Form

Sectioning Technique	Precision (microns)	Typical F/A Uses
Packaged-unit sectioning: Sawing	2000	Gross internal package problems Ceramic Packages
Packaged-unit sectioning: Grinding	500	Assembly problems
Wafer cleaving: Manual	1000	Repeated structure or layer problems
Wafer cleaving: Precision	1.5	Localized structure or layer problems
Die polishing	0.2	Device defects > 0.5 microns
Focused ion beam: Sectioning	0.05	Surface defects or defects < 0.5 microns
TEM sample preparation techniques	0.05	Defects < 0.5 microns requiring high-resolution imaging

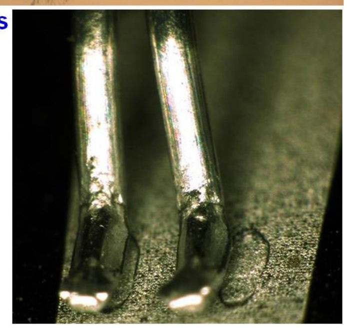
Heel Crack Propagation



Prior to thermal cycle



~ 1700 cycles



- Crack propagated from the stress point created during bonding process
- From bond heel to centre along the plane just above the bonding interface

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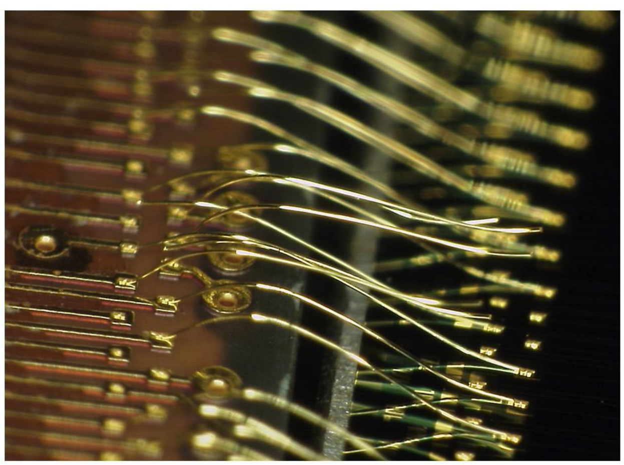
Wire Lifts



Wirebonds and Silicones don’t mix

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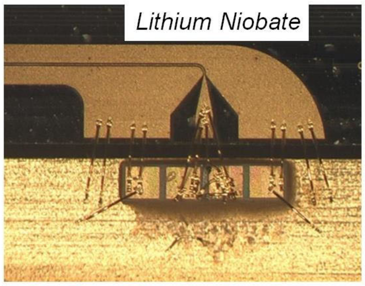
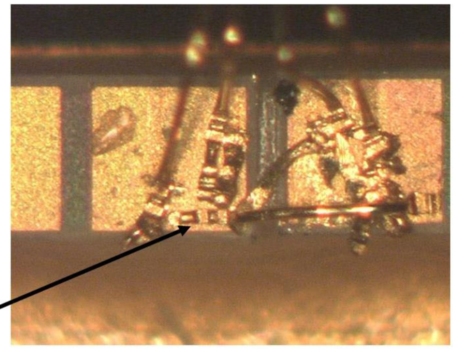
Wirebond Yield Issues Inside Modulator Housing

Enlarged View





Enlarge view of gold wedge bonds inside housing.
Note the multiple bonds attempts to resistor pack.
Yield problems were determined to be the result of silicone RTV contamination on the wirebond surfaces.

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Case History - Fluoridated Bond Pads

- Sources of Fluorine Contamination
  - Storage in Fluoroware/plastic boxes
  - Plasma processing
- Corrective Actions
  - Organic wet resist stripper selectively removes Al(OF)x from bond pad
  - Microstrip 2001, made by OCG, formerly Olin Hunt, contains NMP and amino-ethoxy-ethanol

Grman et.al., Solid State Tech., Feb. (1992) p. 43.

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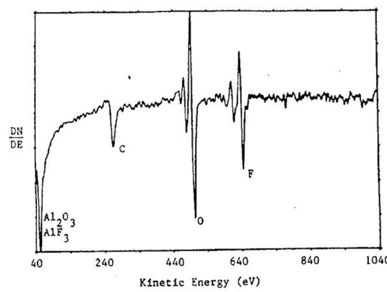
Case History - Fluoridated Bond Pads

Auger survey of fluoridated bond pad



Reproduced with permission of R.K. Lowry, Proc. 1992 ISTFA Conf. p 173

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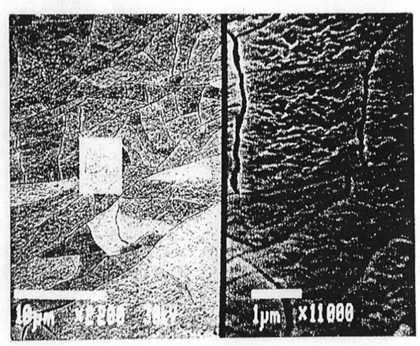
Case History - Fluoridated Bond Pads

SEM micrograph of fluoridated bond pad



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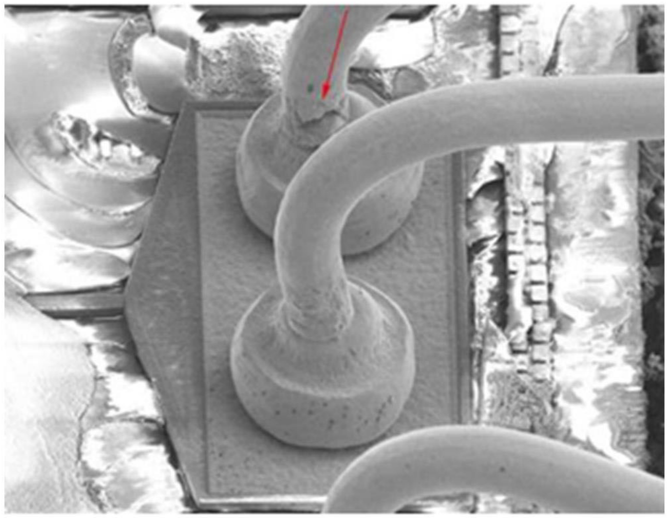
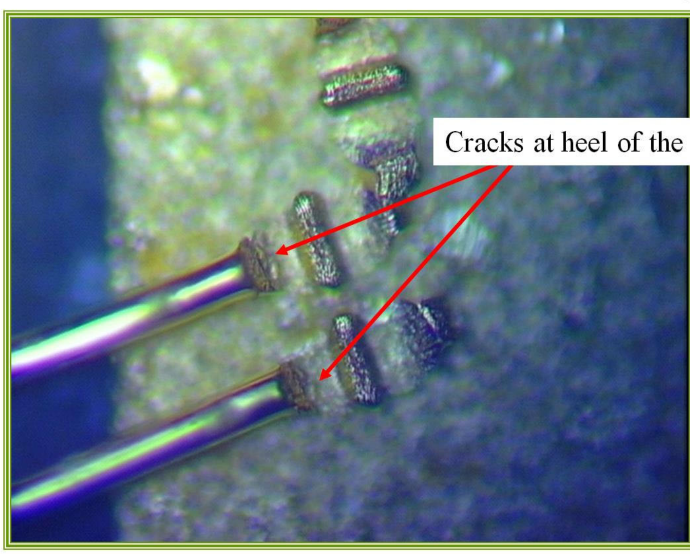
Neck Breaks



 68

Cracked-Lifted Heel (Au Wedge)

REJECT



NOTES: Reject..Photo shows evidence of cracked/lifted bonds, probably due to excessive power/force setting on the wirebonder. Heel cracks are a common problem and difficult to spot.

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Ref. SDL[9]

Defective Platings Cause Problems

➢The photo of the hybrid package on the following slide was identified during assembly and was defective due to improper plating……blisters were contaminants from the plating process
➢The package was intended for use on a Space Program
➢Failure Analysis found the gold plating to be porous and there were many particles on the surface that were oxides of Cu, Zn and/or Fe along with sodium, calcium and chlorine
➢Bake out at 200C under vacuum caused some of the particles to "burst" on the surface and change color
➢The cause and corrective action was to have the entire lot of packages stripped and re-plated

➢Initial Kovar (FE-NI-Co alloy) Plating Spec (typical for a high reel package) was
- ➢50 microinches of Ni Strike per QQ-N-290
- ➢200-300 microinches of sulfamate nickel per AMS 2424B
- ➢50-75 microinches gold per Mil-G-45204, Type III, Grade A

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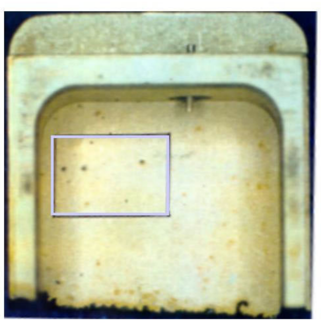
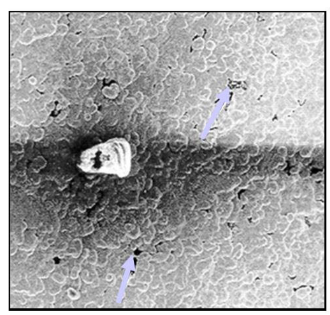
Plating Defects



Housing after 200°C for 2 hours



SEM photo (300 x) of crystalline particles and porosity. EDX spectra showed particles consisted of Ca, Cl, Fe, + O

 81

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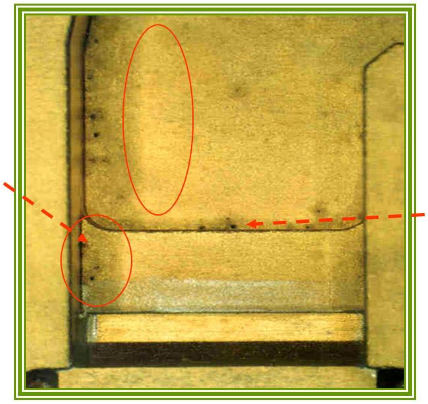
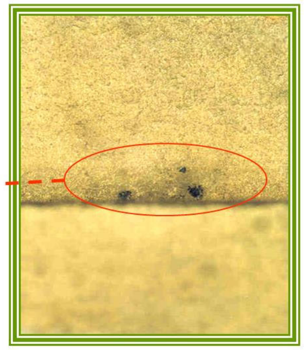
REJECT Plating Blisters Inside Housing

Blisters



Package base in gold plated housing



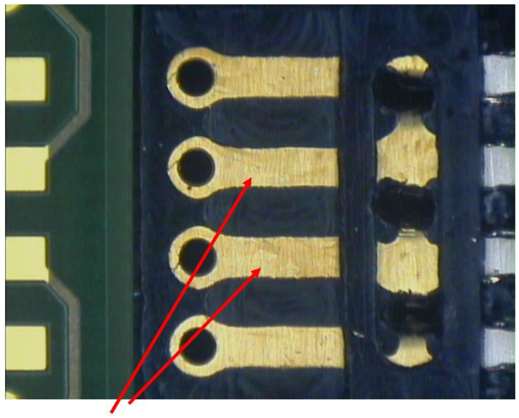
Enlarged View (18 X)

NOTES: Reject..Blisters in plated housing, will interfere with wire and die attach processes.

Typical Plating Requirements

- Package base 100-350 microinches electroless nickel per MIL-C-26074E from a sulphamate bath (AMS 2424B)
- Top layer.. 50 microinches of Au minimum per MIL-G-45204 type III grade A (replaced by ASTM B 488-01)
  - Gold plating not absolutely needed on lid
- Leads plated with electrolytic nickel plate per QQ-N-290
- Plating spec has to accommodate sealing, pins and possible wire bonding to package base
  - Trade offs studies and prototype samples are needed
  - Package geometry can effect plating consistency
- Porosity or even a few PPM of contaminants can effect die bond, wirebond and seal operations

Surface Contamination



"Brownish Stains" on Lead Frame easily detected with AES

Photos above show "brownish" stains on bond pads. This staining is from residual plating solution not properly rinsed after the Au immersion dip.

This kind of contamination will interfere with wirebonding.

Wirebonding to ENEPIG can be problematic

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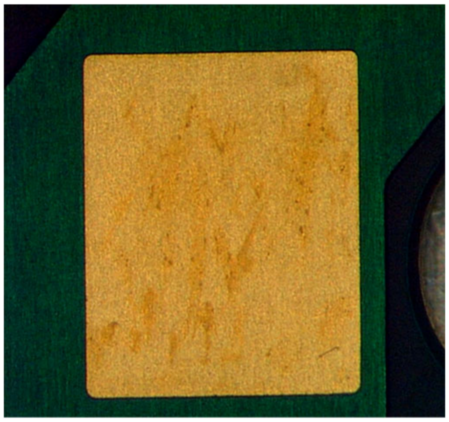
Wirebond Problems due to Poor Plating Processes

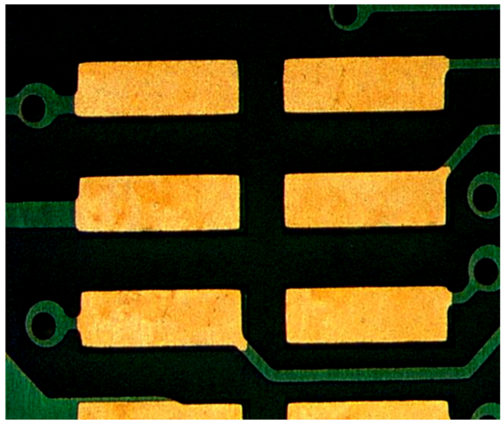
Following defects resulted from a poor a ENIG (Electroless Nickel Immersion Gold) Ref IPC 4552 plating process on FR-4 which was done incorrectly and caused a very serious wirebond problem. The 7 and 15 mil heavy aluminum wirebonds would not stick to the gold plated traces on the FR-4. All the circuit boards in stock had to be pulled and sent out for hydrogen plasma cleaning in order to remove the contamination left from the residual plating chemistries that were left on the surface.

Also shown are other common plating problems.

64

Contaminated FR-4 Traces



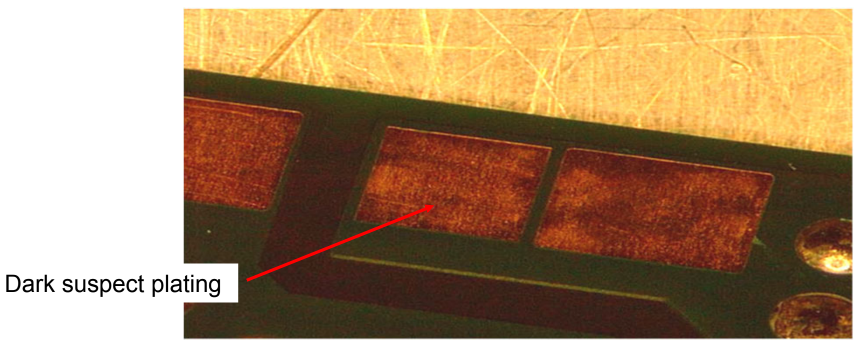


Orange-brownish stains due to improper cleaning at the supplier. PWBs with this type of contamination must be cleaned prior to wire bond and/or solder attach of power chips (40X)

65

65

Visual Defects Platings FR-4

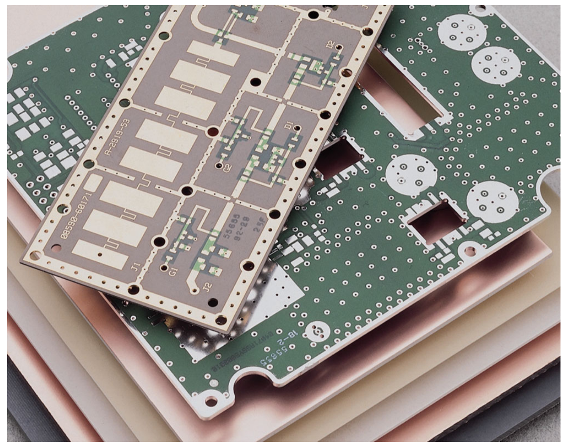


- 2.11 Dark plating on connector board possibly due to corrosion of the nickel under plate during the immersion gold process ("black Pad"). PWB shown above was photographed at an angle under a well lit viewing scope (10X)

66

Duroid (PTFE) Boards

- Copper clad teflon boards with excellent RF properties
- Soft and flexible ..makes die bond and wirebond more of a challenge
- Rogers is a major supplier e.g. RT 5880
- RT 5880 glass fiber reinforced softens with heat



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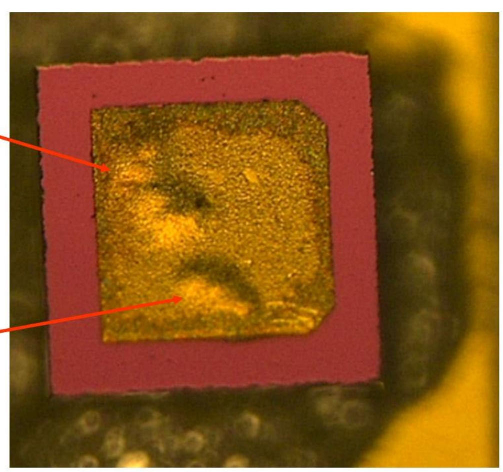
Blistered metal on a Cap



Au blisters

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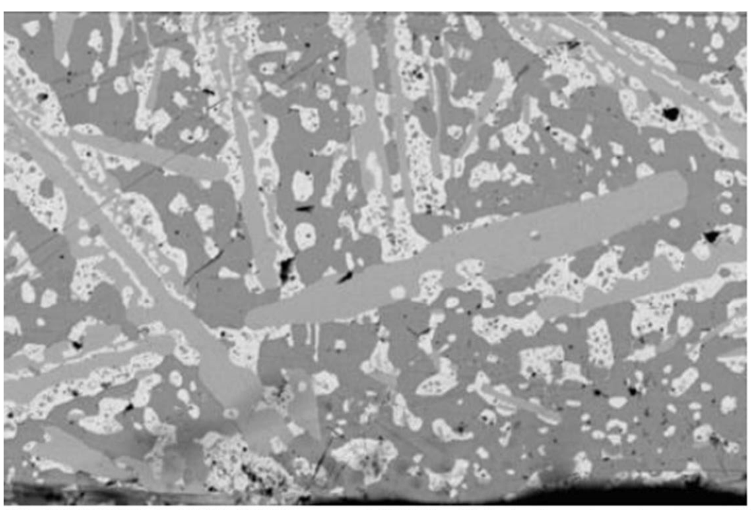
Au Embrittlement

- Often times boards need to be selectively plated for wirebond purposes… which can be costly
- 3% Au in Tin Lead solders is a threshold # above which Gold intermetallics $AuSn_4$ and $AuSn_2$ will form and embrittle the solder joint
- Careful review of the plating specs and solder requirements are required to avoid this costly reliability mistake which many companies seem to relearn year after year

Au Embrittlement (X-sction)



[Ref. IFN 370_5, BSE SEM image, 1513X]. This is the microstructure of the solder joint showing the distribution of Sn-phase (dark gray), Pb-phase (light gray) and Au-Sn IMC (intermediate gray). Image analysis suggests the Au-Sn IMC is ~28% area fraction. EDS results gave ~ 10 wt% Au, which is ~3X the

Loose Conductive Particles and Murphy's law

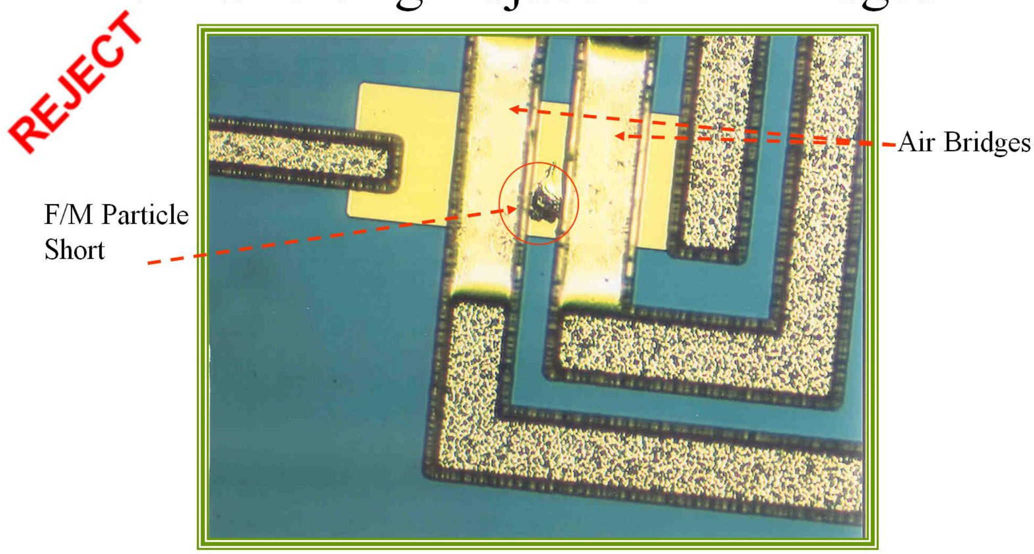
Murphy's Laws

1. In any field of endeavor, anything that can go wrong, will go wrong.
2. Left to themselves, things always go from bad to worse.
3. If there is a possibility of several things going wrong, the one that will go wrong, is the one that will cause the most damage.
4. Nature always sides with the hidden flaw.
5. If everything seems to be going well, you have obviously overlooked something.

Foreign Material Contamination

- Foreign Material Identification and Control
  - provision is intended to identify, control and eliminate foreign material that enters the manufacturing flow
  - unattached or partially attached material is a problem... can break loose and short two adjacent active conductive paths
  - Residual flux or contamination left in a package that can contribute to a corrosion process

F/M Shorting Adjacent Air Bridges



NOTES: Reject..Photo clearly shows an opaque particle (assumed to be conductive) shorting adjacent air bridge structures, particle was verified as attached; (i.e. 20 PSIG of dry air couldn't dislodge the particle) (400X)

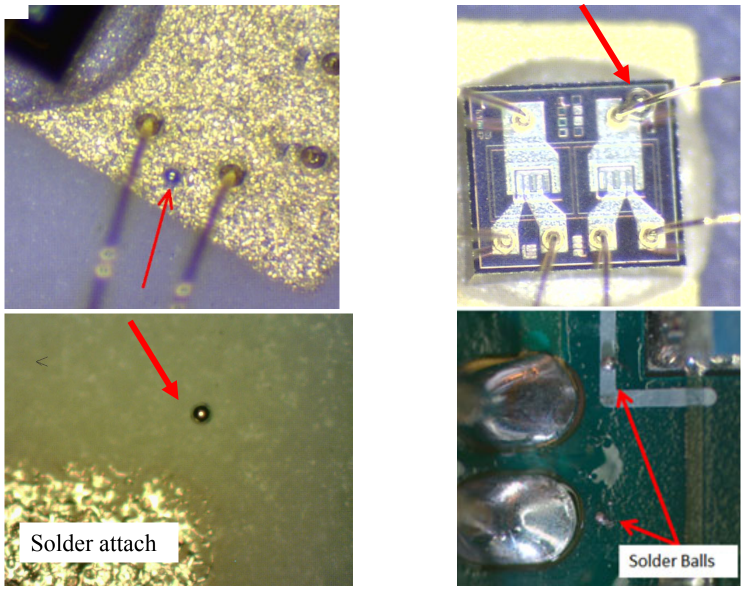
PIND Particle Impact Noise Detection (TM 2020.8 June 2004)

Watch Video

- Non-destructive means of detecting for loose particles inside a cavity
- Challenge for FA to capture and remove particle
- Historically produced many false readings due to fixturing or difficulty in getting a repeatable baseline
- Some companies use the PIND tester to clean parts (Pre PIND) before PIND testing
  - Mount parts upside down on shaker prior to seal

REJECT

Solder Balls



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MOISTURE IN PACKAGES

Factors affecting moisture-related fail modes

- Moisture concentration
- Hydrogen concentration
- Sealing environment
- Choice of package and cavity materials
- Pre-seal cures, bakes, etc.
- Materials outgassing
- Seal integrity
- Leakage rate
- Gaseous permeation
- Humidity of external ambient
- Cleanliness of surfaces
- Passivation integrity
- Interior surface physics/ surface energy
- Type(s) of metallization
- Operating temperature
- Temperature cycling
- Type of device
- Device electrical characteristics
- Package headspace pressure
- Test protocols
- Power dissipation
- Duty cycle
- Product shipping/storage conditions
- Service life expectation

Ref: B. Lowry CMSE 2011

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Why does a Package need to be Hermetic?

- If liquid droplets form on the surface of an IC or MEMS device, the water (H_2O) combined with ionic contamination along with a bias can adversely affect the device..namely
  - Chemical corrosion … exposed aluminum wires or Al metal at bond pads
  - Ag and Au dendritic growth
  - Leakage across pins
  - "Stiction" in a MEMS, early wearout, performance variation if vac packed
  - Changes in dielectric constant on waveguides used in RF MEMS
  - Protection from particles and outside contamination
  - Damage to the doped layers on a silicon chip if the surface passivation isn't good enough
- Moisture droplets can form as the package is cooled below the dew point within the package or if frost has formed on the chip and the package is then warmed
- The "Hermeticity Paradigm"

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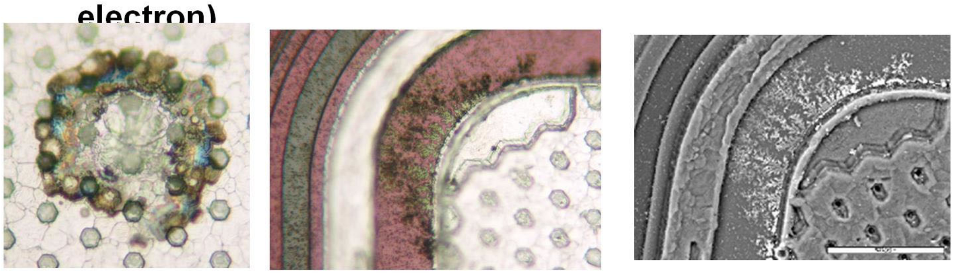
Moisture Related Failure Mechanisms

Die level:

- **Corrosion of Al metallization.**
- **Dendrites between metallization lines.**
- **Leakage currents.**
- **Charge instability (lateral, ion drift, hot electron)**



HEXFET failures

Ref: C.Greenwell 107

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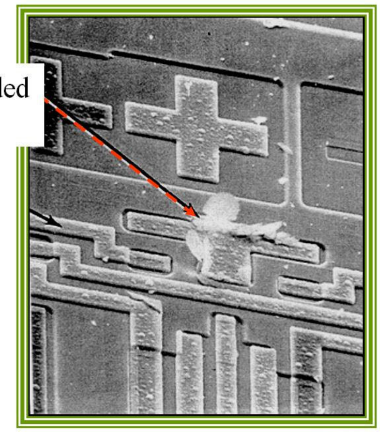
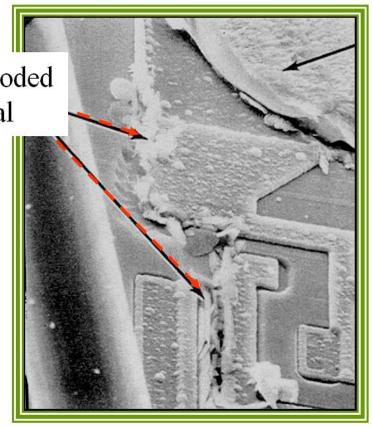
Corrosion on an IC Die



550 X



800 X

NOTES: Reject.. Corroded aluminum metal lines on an IC die shown at two different magnifications

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Aluminum Metal Corrosion Reaction

- Halogens + Moisture + Metals that differ widely in the electrochemical series potentials

$$Al\,(OH)_3 + CL^- \longrightarrow Al\,(OH)_2 + OH^-$$

$$Al + 4CL^- \longrightarrow Al\,(CL)_4^- + 3e^-$$

$$2AlCL_4^- + 6H_2O \longrightarrow 2Al(OH)_3 + 6H^+ + 8CL^-$$

The chlorine ion is liberated and available to continue the corrosion process.....this is bad news and the reason why just minute amounts of ionic contamination can cause failures downstream

Consensus is that 3 monolyaers of water is needed to promote corrosion , given a sufficient amount of ionic contamination present

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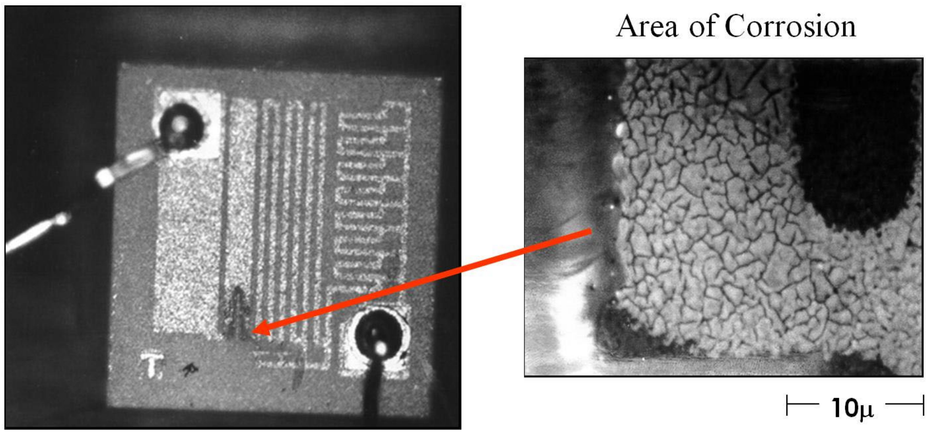
Corrosion Failures on a Chip Resistor



(Enlarged View 3000X Backscatter SEM Image)

Optical photo of a NiCr unpassivated chip resistor (100 x)

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Ref: Gidep #F3-A-94-03

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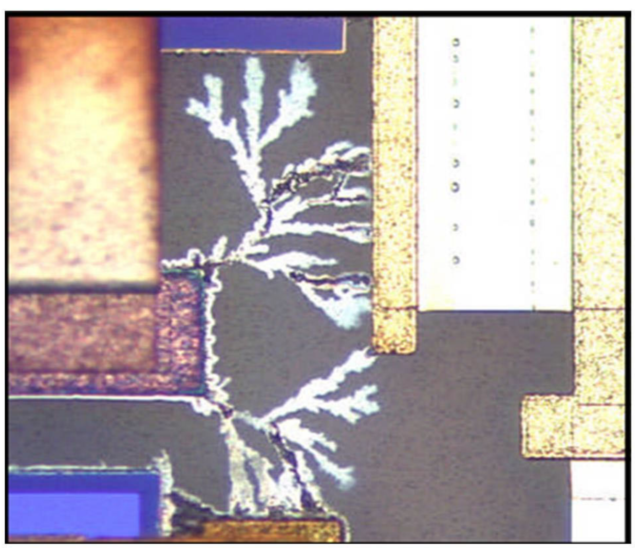
Silver Dendrites and Short Circuits



Ref : "Electrolytic Electromigration of Metallic Material and Silver Filled Epoxy" IEEE Transactions on Reliability, Vol 44, No. 4, 1995 December

Space Shuttle Launch Abort Due to Spittle

SPITTLE VIDEO

- In 1984 a Space Shuttle launch had to abort in the final countdown because of a failure of an IC in an on-board computer.
- After an extensive FA investigation the root cause of failure was traced to human contamination that had dried onto the surface of the IC and caused corrosion and an open circuit condition.
- Spittle and other forms of organic contaminants contain ions such as chlorine (Cl) and potassium (K) and sodium (Na), which combine with moisture to corrode aluminum metal.
- Identification and elimination of human contamination inside a hybrid is part of the inspection process

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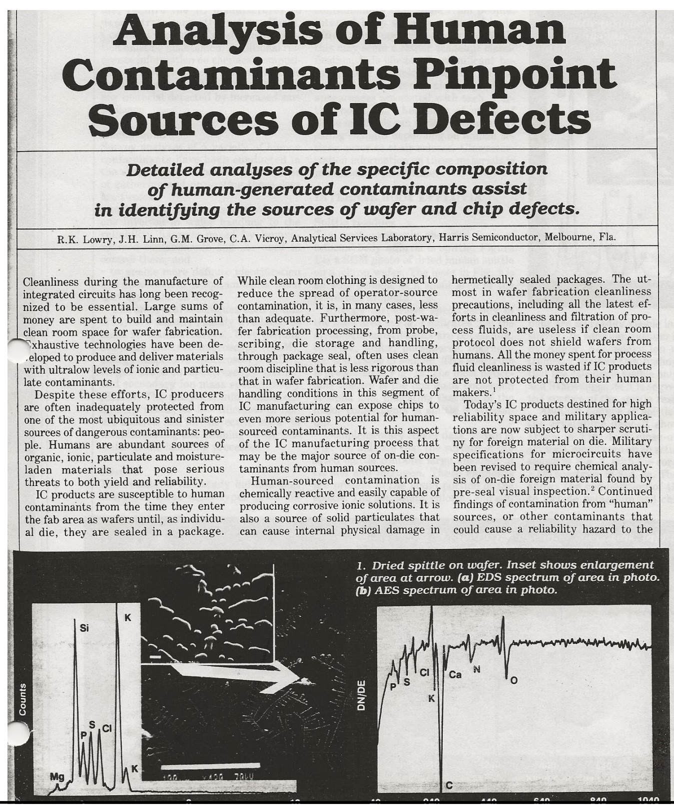

Analysis of Human Contaminants Pinpoint Sources of IC Defects

Detailed analyses of the specific composition of human-generated contaminants assist in identifying the sources of wafer and chip defects.

R.K. Lowry, J.H. Linn, G.M. Grove, C.A. Vicroy, Analytical Services Laboratory, Harris Semiconductor, Melbourne, Fla.

Cleanliness during the manufacture of integrated circuits has long been recognized to be essential. Large sums of money are spent to build and maintain clean room space for wafer fabrication. Exhaustive technologies have been developed to produce and deliver materials with ultralow levels of ionic and particulate contaminants.

Despite these efforts, IC producers are often inadequately protected from one of the most ubiquitous and sinister sources of dangerous contaminants: people. Humans are abundant sources of organic, ionic, particulate and moisture-laden materials that pose serious threats to both yield and reliability.

IC products are susceptible to human contaminants from the time they enter the fab area as wafers until, as individual die, they are sealed in a package. While clean room clothing is designed to reduce the spread of operator-source contamination, it is, in many cases, less than adequate. Furthermore, post-wafer fabrication processing, from probe, scribing, die storage and handling, through package seal, often uses clean room discipline that is less rigorous than that in wafer fabrication. Wafer and die handling conditions in this segment of IC manufacturing can expose chips to even more serious potential for human-sourced contaminants. It is this aspect of the IC manufacturing process that may be the major source of on-die contaminants from human sources.

Human-sourced contamination is chemically reactive and easily capable of producing corrosive ionic solutions. It is also a source of solid particulates that can cause internal physical damage in hermetically sealed packages. The utmost in wafer fabrication cleanliness precautions, including all the latest efforts in cleanliness and filtration of process fluids, are useless if clean room protocol does not shield wafers from humans. All the money spent for process fluid cleanliness is wasted if IC products are not protected from their human makers.[1]

Today's IC products destined for high reliability space and military applications are now subject to sharper scrutiny for foreign material on die. Military specifications for microcircuits have been revised to require chemical analysis of on-die foreign material found by pre-seal visual inspection.[2] Continued findings of contamination from "human" sources, or other contaminants that could cause a reliability hazard to the

1. Dried spittle on wafer. Inset shows enlargement of area at arrow. (a) EDS spectrum of area in photo. (b) AES spectrum of area in photo.

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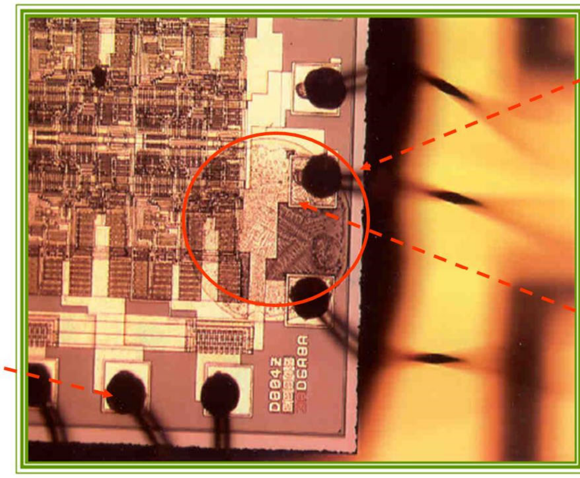
Spittle on IC

REJECT

Watch Video



NOTES: Reject ..Enlarged view from previous slide . Photo shows human contamination on IC , possibly a long term reliability problem, may cause current leakage between pins (400X)

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Hermeticity Testing per MIL-STD-883 Test Methods

- **Seal (TM 1014)**
  - Designed to determine the integrity of a hermetically sealed device
  - Fine and Gross test leak methods defined
- **Internal Water Vapor Content (TM 1018)**
  - Identifies gases internal to a hermetically sealed cavity also known as RGA
- These two tests are closely tied together!

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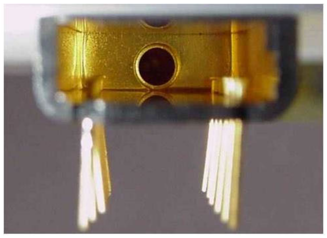
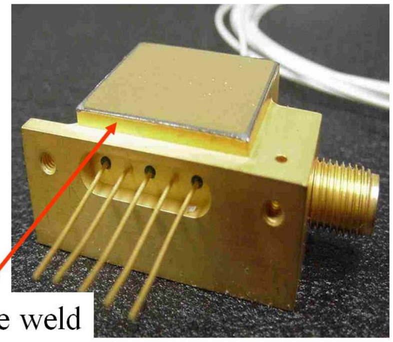
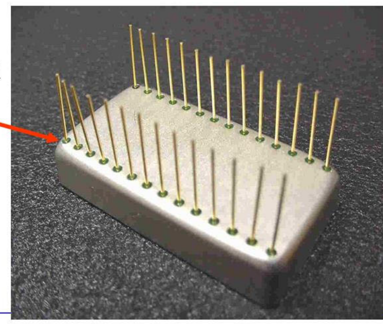
Sources of Leaks in Packages





Along the weld

At the glass to metal feedtrough



Or through a defect
in the package itself

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Residual Gas Analysis

- Mil STD-883F Test Method 1018.4 dated 18 June 2004
- Puncture cavity and suck out gases into quadrupole mass spec for analysis to determine relative abundance as a function of their mass/charge ratio
- Moisture limit 5000 PPM provides for a dew point below the freezing point at 1 atmosphere
- Sources of moisture in a package
  - From ambient…i.e. package leaks
  - From internal outgassing of epoxies and organics
  - From within the seal chamber itself
- Hydrogen gas and other harmful gases

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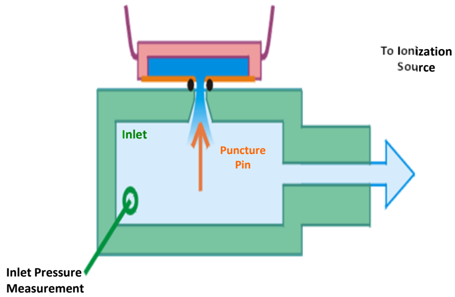
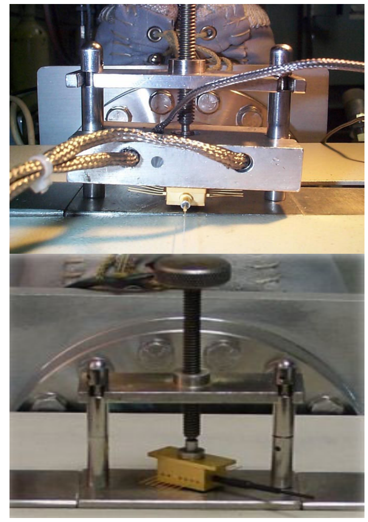
MASS SPECTROMETRY

Mount - Heat - Puncture

Transfer Gas to Detector





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FA cautions prior to RGA puncture

- It's often difficult to recreate a moisture related failure mode, but once the cavity is punctured the atmosphere that existed during the failure is no longer available.
- Confirm hermeticity prior to test…realize a leaker may be plugged doe to organic board coatings
- Bake out part and see if symptom goes away
- RGA normally involves an overnight bake out …may not be applicable in a FA sequence
- Be sure to carefully study the other gas constituents

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RGA Issues with Hermetic Packages

- Organic impurities outgassed from epoxies and other materials have been the cause of failures in opto pump lasers
- Hydrogen outgassing may contribute to die level metal hydride formation and thus affect device performance
- Trace amounts of organic residue could prove fatal to fiber ends, lens and other sensitive surfaces
- High moisture concentrations (above 5,000 PPM) may lead to condensation on sensitive surfaces (e.g. lens, surface of the waveguide)
- Hydrogen reaction with oxides in the package such as NiO, or AgO to form moisture (Highly negative Gibbs Free Energy calculation). Free hydrogen and oxygen chemical reaction less likely to occur.

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RGA Data Analysis

- Although moisture is the only gas spec TM 1018 (<5,000 PPM) and the primary there are many other gases that are measured and reported which are useful for Process Control
- *Nitrogen*….main gas used in sealing chamber ranges from 78% for dry air to 99% for pure N2
- *Oxygen*…watch closely since oxygen may be consumed when reacting with carbonaceous material generating moisture and carbon dioxide. Oxygen can also combine with Hydrogen to produce moisture
- *Argon*...detectable in small amounts (<500PPM) in nitrogen sealing gas. In dry air it's about 9200 PPM and the ratio of Oxygen/Argon ration is about 20/1
- *Carbon Dioxide*…generated during thermal degradation of organic material
- *Hydrogen*…may be intentionally added to create a reducing atmosphere or evolve from the package platings and base alloys up to several percent.
- *Helium*…the presence of helium indicates a leak test escape or helium was intentionally added to the sealing atmosphere as a tracer gas (10 % typical)
- *Flourocarbons*..the presence of gross leak flourocarbons indicates the package was non-hermetic and/or the result of residual cleaning solvents
- *Other Gases*…are an indication of process control. Residual cleaning solvents, photoresits material, vacuum pump oils etc can all be detected using RGA

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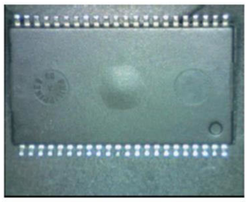
ESD/EOS FAILURES

EOS External Damage

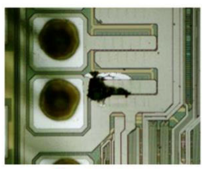


Package Bulge

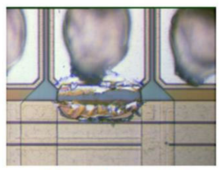
Package Hole

Package Burnt/Cracked

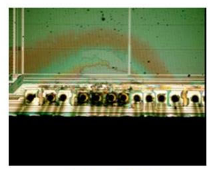
EOS Internal Damage



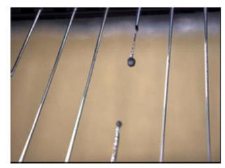
Burnt Metal



Open Connection



Heat Stress



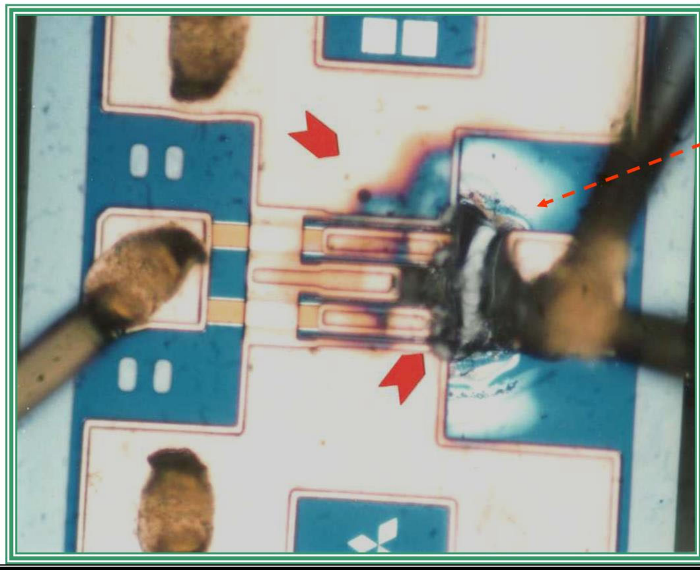
Melted Bond Wire

http://www.cypress.com/?rID=40421

ESD/EOS FAILURES 1

- ~25-35% of electronic failures are EOS/ESD
- High burden for semiconductor and board assembly
- Failure % has remained the same over many years
- Difficult to identify
- Finger pointing about who is responsible
- Often not systematic
- Root cause hard to find

EOS Blown Output on GaAs FET



Electrical Overstressed Area

NOTES: Shorted and blown junctions, due to the gap welding process. Remove and replace FET

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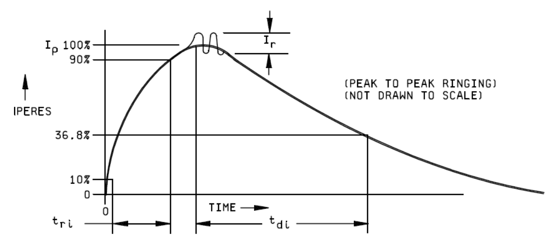
ESD Susceptibility to Device Type

DEVICE	RANGE THRESHOLD VOLTS
1- MOSFET	10 TO 100
2- V-MOS	30 TO 1,800
3- N-MOS	60 TO 500
4- GaAsFET	60 TO 2,000
5- EPROM	100 TO 500
6- JFET	140 TO 7,000
7- SAW	150 TO 500
8- OPAMP	190 TO 2,500
9- CMOS	150 TO 3,000
10- 256 K DRAM	200 TO 3,000
11- SCHOTTKY DIODES	300 TO 2,500
12- FILM RESISTORS	300 TO 3,000
13- BIPOLAR TRANSISTOR	300 TO 7,000
14- ECL	500 TO 2,000
15- SCR	500 TO 1,000
16- SCHOTTKY TTL	500 TO 2,500

ELECTROSTATIC DISCHARGE SENSITIVITY CLASSIFICATION (TM 3015)

- This method establishes the procedure for classifying microcircuits according to their susceptibility to damage or degradation by exposure to electrostatic discharge (ESD). This classification is used to specify appropriate packaging and handling requirements in accordance with MIL-PRF-38535, and to provide classification data to meet the requirements of MIL-STD-1686.
- Human Body Model



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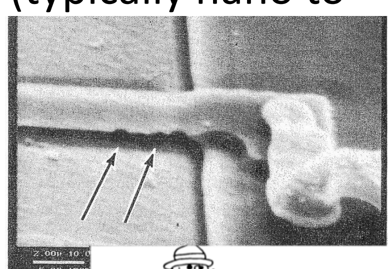
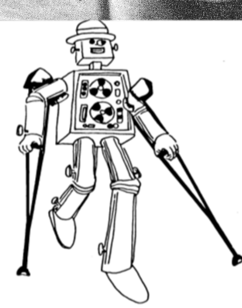
ESD Damage

Defined as: a **limited energy**, **high voltage** **short time duration pulse** (typically nano to microseconds in length).



Not Easily Visible

- Gate oxide breakdown
- Junction spiking
- Latch up



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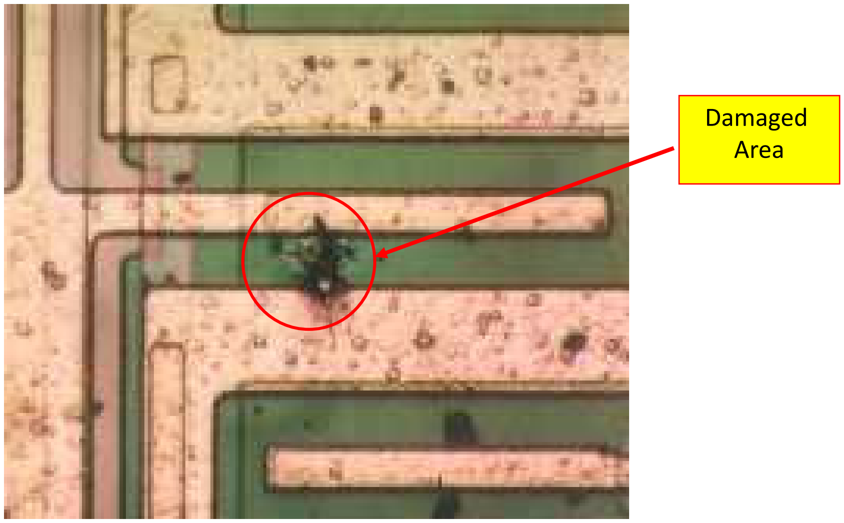
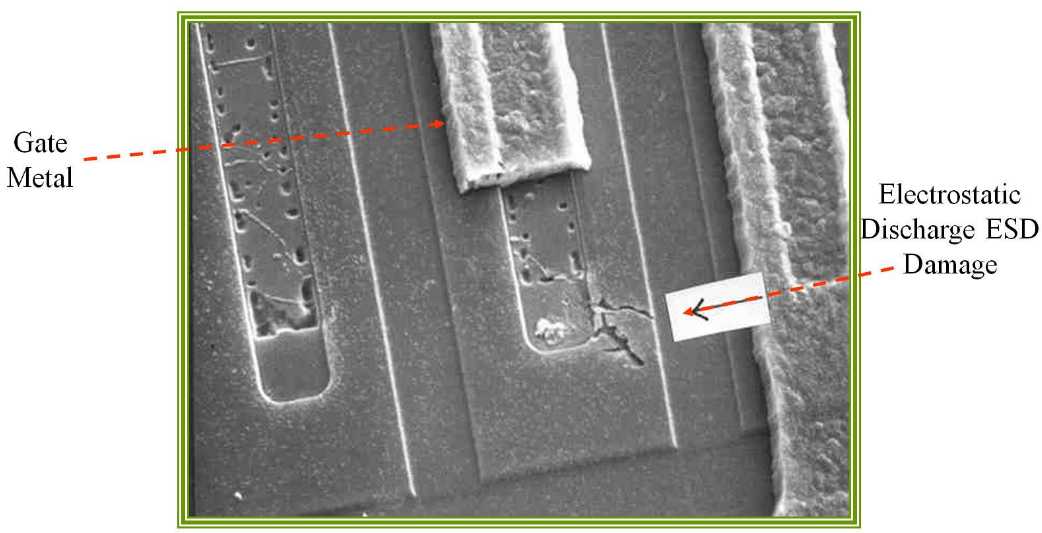
ESD Damage Site in MOS IC

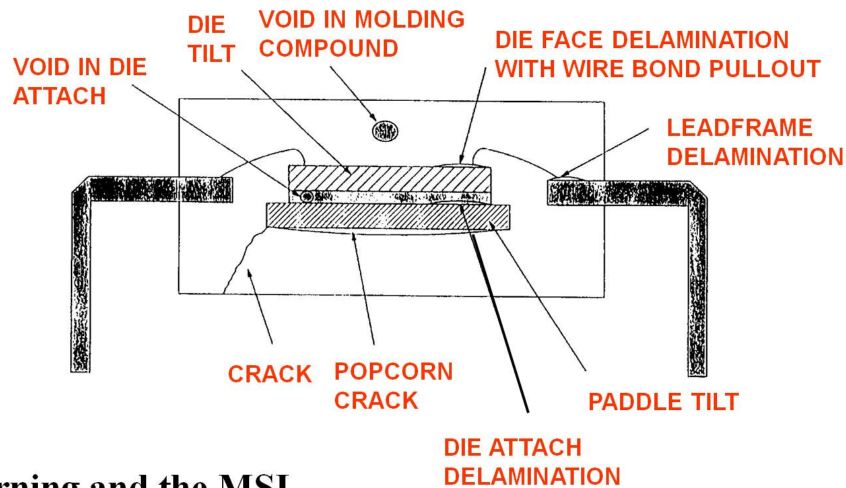


ESD Damage Site



NOTES: Reject ..Electrostatic Discharge (ESD) normally not seen with an optical microscope. This SEM photo shows and ESD damage site in the gate oxide, the metal was removed. (2000X)

Typical Plastic Package Defects



Popcorning and the MSL Levels

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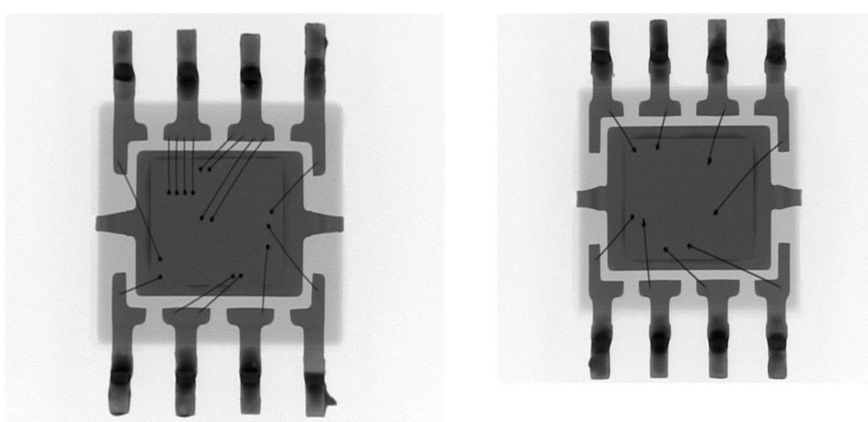
How to spot a counterfeit part

Two units externally identical with same part number and same date code



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ELECTRONIC COMPONENT FAILURES AND MATERIALS ANALYSIS

- **Visual**
  - Optical, SEM, TEM
- **Chemical**
  - EDS, Auger, SIMS, XPS, FT-IR
- There are numerous others.
- Not all methods apply for every FA.
- Choice of method(s) dictated by nature of failure, structure of device, etc.

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ELECTRONIC COMPONENT FAILURES AND MATERIALS ANALYSIS

ANALYTICAL METHODS IN FA

- Root cause identification requires analyzing the bad vs the good, comparing a failed unit to a good unit.
- Sometimes this comparison can be done using a unit of identical structure that is known good.
- Sometimes the comparison must be done by analyzing materials of composition used to manufacture product, versus specification.
- Be aware:
  - FA investigations often provide answers…
  - They can also raise even more questions…
  - Sometimes more questions than answers.

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Optical Low Mag Inspect

Stereo Zoom Microscope

Very important to document the ”as-received” condition of any samples received

High Mag Optical Microscopes

- Bright Field
  - Light goes directly through the objective lens and reflects from the sample’s surface. Bright view is used to view an object’s surface.
- Dark Field
  - Light is directed to the sample at a low angle. By adjusting the focus, an observer sees reflections from the surface and objects below the surface if the sample’s matrix is transparent. Dark field can be used to determine if a particle is embedded.
- Polarized Light
  - Polarized light is directed to the sample. Interference contrast is used to find objects.

Dimensions and Measurements

A word about length: The term mil and micron are commonly used. Both refer to a unit of length.

A mil is one thousandth of an inch.
1 mil = 0.001 inch = 25.4 microns
A micron (µm) is one millionth of a meter.
1 micron (1 µm) = 1/1,000,000 meter = 10,000 Å = 0.04 mils

Typical dimensions of components found within a Hybrid circuit:

Minimum dist from top of package to pin	40 mils
Thickness of a ceramic substrate	25 mils
Width of a Thick Film Conductor	10 mils
Gold Wire diameter	1 mil
Thickness of to Au Plating	50 microinches
Transistor gate length on IC	.22 microns

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OPTICAL MICROSCOPY RESOLUTION

Resolution of an optical microscope is the shortest distance between two points on a specimen that can still be distinguished by the observer or camera system as separate entities.

Wavelength (Nanometers)	Resolution (Micrometers)
360	.19
400	.21
450	.24
500	.26
550	.29
600	.32
650	.34
700	.37

Best optical microscope resolution is about 0.3 micrometers

0.3 micrometers = 300 nanometers
0.3 micrometers = 3000 Angstroms

SPATIAL RESOLUTION CONVERSION FACTORS

https://www.onlineconversion.com/length_all.htm

	NANOMETERS nm	MICRONS um	ANGSTROMS Å
NANOMETERS	-	0.001	10
MICRONS	1000	-	10,000
ANGSTROMS	0.1	0.0001	-

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Electron Microscopy

TYPES:

- Scanning electron microscope (SEM)
- Field emission scanning electron microscope (FESEM)
- Environmental scanning electron microscope (ESEM)
- Auger electron microscope (AEM)
- Transmission electron microscope (TEM)

ASSOCIATED TECHNIQUES:

- Voltage contrast (CV)
- Focused ion beam (FIB)
- X-ray energy dispersive spectroscopy (EDS)
- X-ray wavelengths dispersive spectroscopy (WDS)

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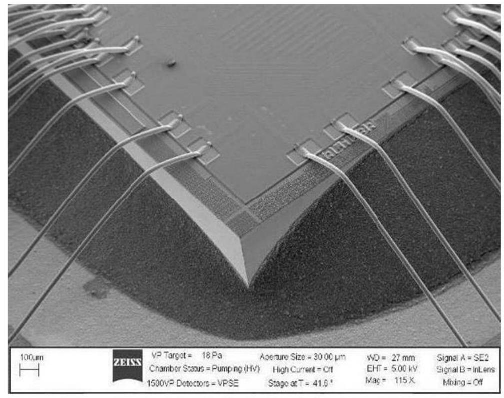
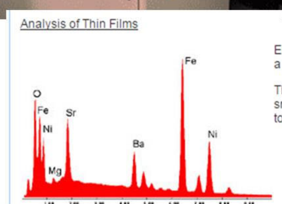
Scanning Electron Microscope (SEM)





High resolution images such as the one shown above are obtained in the SEM along with elemental information. Some parts are coated with carbon to avoid "charging".

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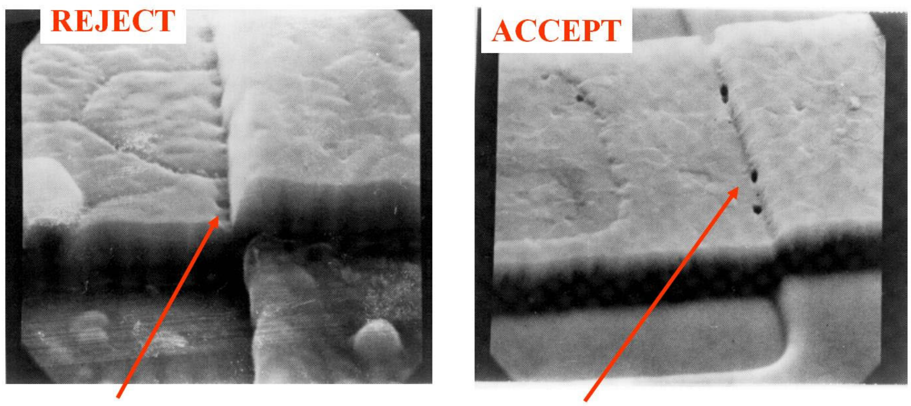
SCANNING ELECTRON MICROSCOPY

- **Produces images of a sample by scanning the surface with a focused beam of electrons.**
- **Electrons interact with atoms in the sample, producing signals containing information about the surface topography and composition of the sample.**
- **Best attainable SEM feature resolution is in the range of 0.4 to 20nm, ≡ 4 to 200Å, and ≡ 0.0004 to 0.02 micrometer.**

SEM Inspection per TM 2018



Thinning at the Passivation step less than 50% (7,200x)

Voiding at the Passivation Step (3,400X)

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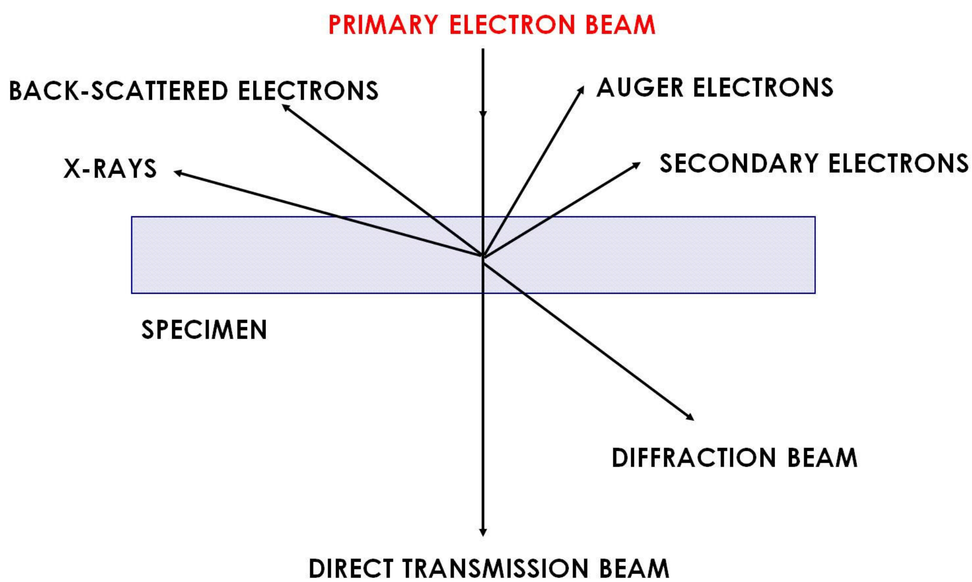
Signals Created by the Interaction of High Energy Electrons with a Specimen



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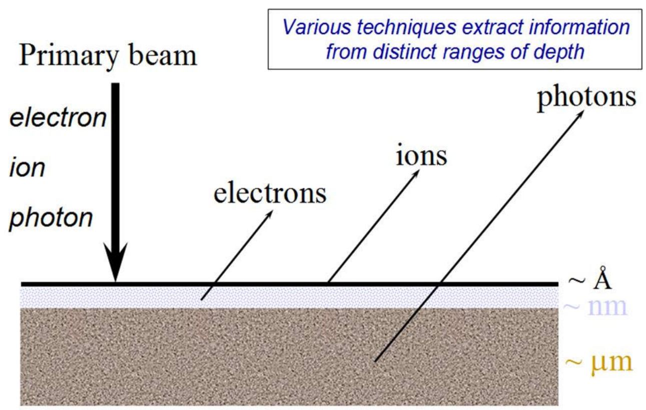
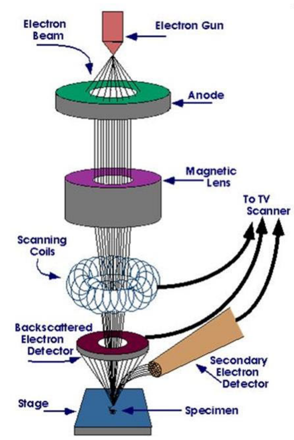
Surface Sensitivity





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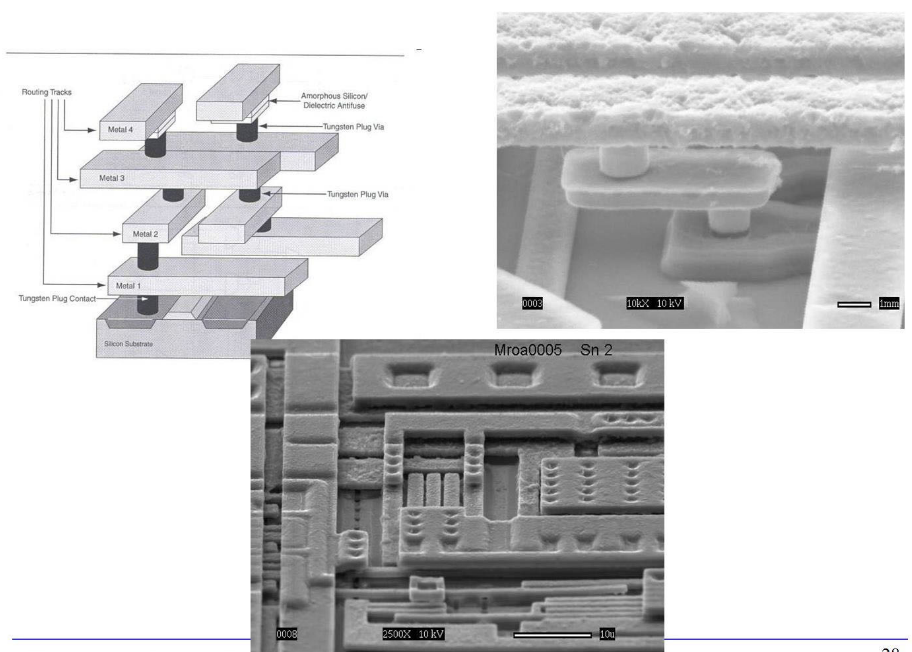
Metallization Technology



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SCANNING ACOUSTIC MICROSCOPY

- Focuses sound waves to image samples.
- For sound wave transmission sample must be immersed in a coupling liquid, most often water or isopropyl alcohol.
- Very effectively used for locating discontinuity-type defects in assembled components such as voids, interfacial delaminations, cracks, etc.
- Can be used in a number of different "modes" depending on sample condition and information needed.

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COMPARISON OF IMAGING RESOLUTION

Method	Best Lateral Resolution, um	Best depth Resolution, um	Typical Scanning Time, minutes
Infrared	250	250	3
X-Ray	10	>2	30
Scanning Acoustic Microscope	<1	1	2-8
Optical Microscope	0.3	1	5
Transmission Electron Microscope	0.1 nm	50 nm	60

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TRANSMISSION ELECTRON MICROSCOPY

- Electron beam is transmitted through a specimen to form an image.
- The specimen is most often an ultrathin section less than 100 nm thick or a suspension on a grid.
- Image formed from the interaction of the electrons with the sample as the beam is transmitted through the specimen.
- Best attainable TEM feature resolution is ~ 1nm, ≡ ~10Å, and ≡ ~0.001 micrometer.

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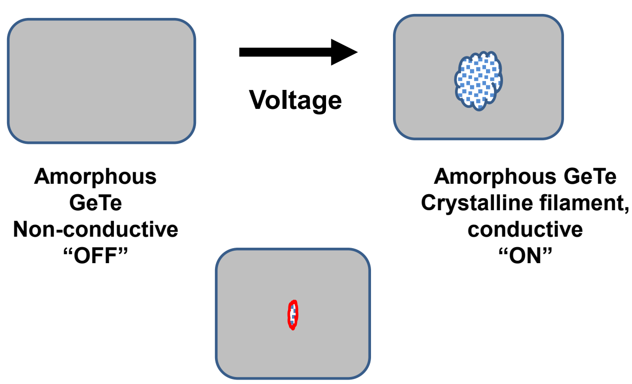
CHALCOGENIDE GLASS MICROSWITCHES



Voltage off. Should revert to fully amorphous non-conductive GeTe.
Vestigial conductive filament always remained. Never fully "OFF".

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MATERIALS ANALYSIS – COMPOSITION AND CONTAMINATION IDENTIFICATION

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ENERGY DISPERSIVE SPECTROSCOPY (EDS)

- Interaction of an electron beam with sample material produces characteristic X-rays.
- X-rays are detected with an energy dispersive analyzer.
- Position of X-rays on the energy spectrum uniquely identifies chemical elements.
- EDS carried out with analyzers added on to SEMs.
- Probably the most commonly used chemical ID tool for electronic components.

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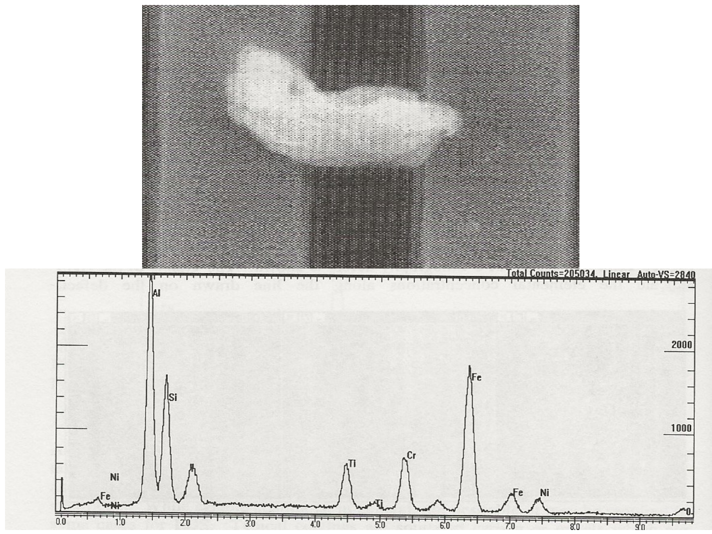
CHEMICAL ANALYSIS - EDS



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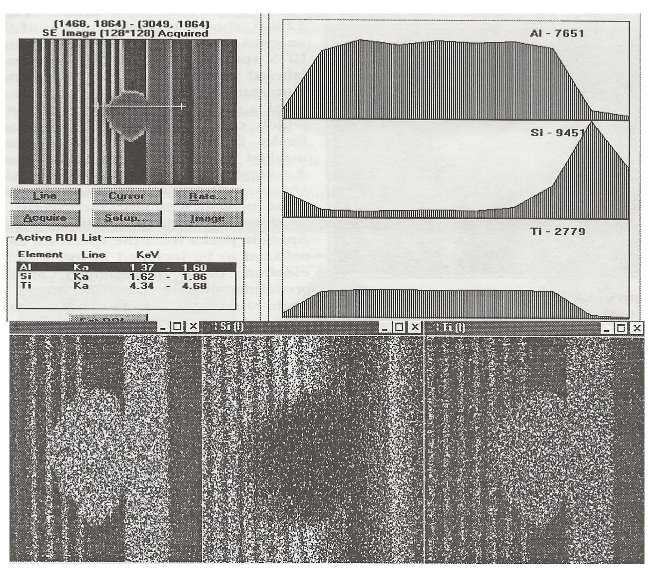
CHEMICAL ANALYSIS - EDS



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AUGER ELECTRON SPECTROSCOPY; (AES)

SCANNING AUGER MICROPROBE

- Say Oh-zhay (not Aww-grrr).
- A beam of 2-25KeV primary electrons bombards the solid surface of a sample.

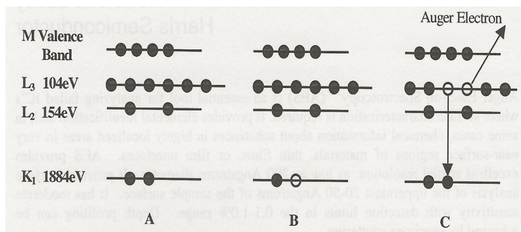

Figure 13.1. Electronic structure of silicon (A) is shown with the configuration after vacancy creation (B) and Auger Transition (C).

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AUGER ELECTRON SPECTROSCOPY (AES)

- Auger electrons ejected from atoms leave with energies in the range of a few eV to 50KeV, characteristic of the electronic environment of their parent atom.
- The energy spectrum provides chemical element identification.
- Analytical spot size (spatial resolution) much smaller than EDS, in the range of ~200Å.
- Escape depths of Auger electrons from near-surface thickness increments of material range from ~20-50Å.
- Thus, Auger is a surface or near-surface analytical technique.
- Detection limits for most elements in the 0.1-1.0% range.
- By ion-milling and removing material from the sample surface using gases like argon, as the Auger analysis process proceeds, a chemical depth profile of the sample is obtained.

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AUGER ELECTRON SPECTROSCOPY

- **Examples of Auger depth profiling “good” and “bad” samples.**
- **Two Silicon Tantalum IC resistors (STIC resistors), 20 nm thick.**
  - **Resistor sample (a) stable and operated normally.**
  - **Resistor sample (b) unstable.**
  - **Oxide incorporated with Ta thru full thickness of the unstable resistor.**
- **Two IC via structures**
  - **High resistance via.**
  - **Normal via.**
  - **Residual carbon film present on high resistance via.**

AUGER ELECTRON SPECTROSCOPY

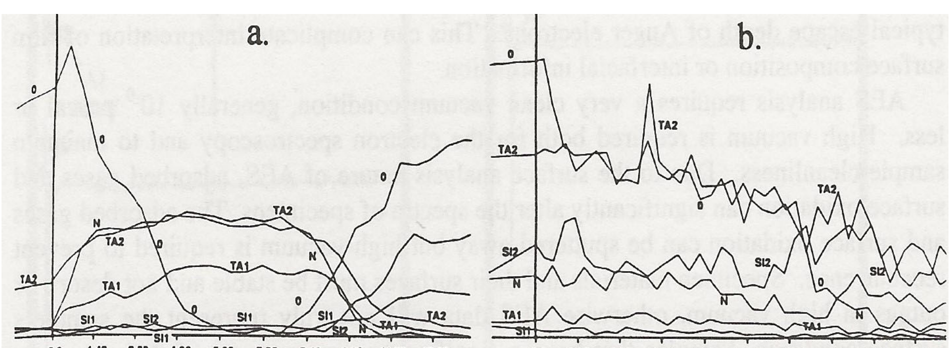
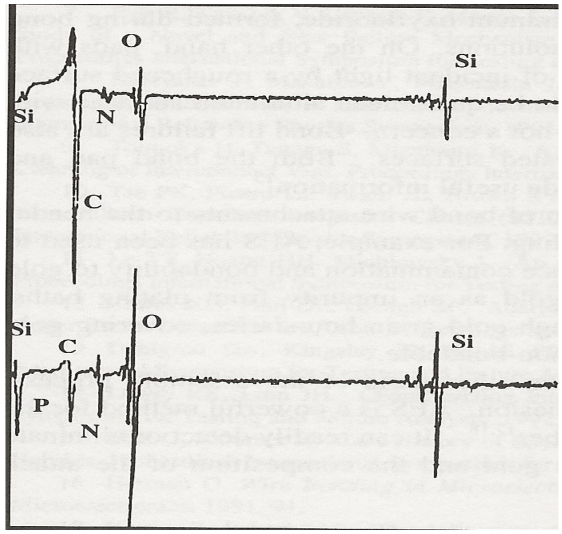


Figure 13.4. AES depth profiles (relative intensity versus sputter time) of STIC resistors, showing discrete TaN with no incorporated oxide in a good resistor (a.) and oxide incorporated in throughout the bad resistor (b.).

AUGER ELECTRON SPECTROSCOPY



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SECONDARY ION MASS SPECTROMETRY (SIMS)

- Primary beam of ions, 10-20 keV, erodes atoms from a solid sample surface.
- Charge exchange near the surface ionizes removed atoms to positive or negative ions, called secondary ions.
- Secondary ions are extracted by an electrical potential and analyzed by their mass in a mass spectrometer.
- The mass spectrum enables elemental or molecular identification of the secondary ions.
- Atomic concentration detection limits in ppm to ppb range.
- Current density of primary ion beam enables milling of sample surface, so SIMS can be both a surface analysis and depth profiling analysis method.

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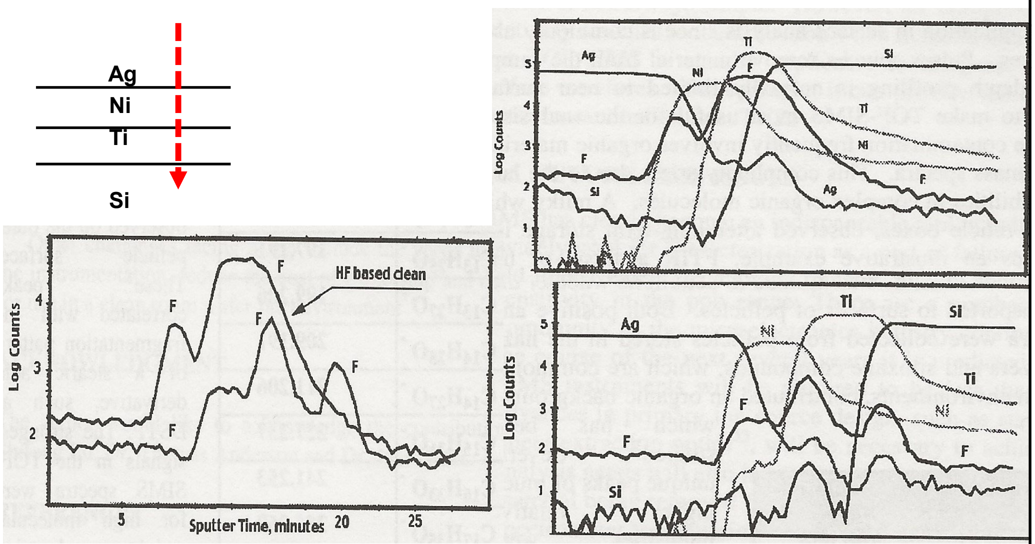
SECONDARY ION MASS SPECTROMETRY (SIMS)



SECONDARY ION MASS SPECTROMETRY (SIMS)

Organic materials analysis

Measured Mass	Formula	Calculated Mass
127.036	$C_6H_7O_3^-$	127.039
197.20	$C_{13}H_{25}O^-$	197.191
199.21	$C_{13}H_{27}O^-$	199.206
209.15	$C_{14}H_{25}O^-$	209.191
211.22	$C_{14}H_{27}O^-$	211.206
227.25	$C_{15}H_{31}O^-$	227.237
241.27	$C_{16}H_{33}O^-$	241.253
255.31	$C_{17}H_{35}O^-$	255.269
267.33	$C_{18}H_{35}O^-$	267.269
269.33	$C_{18}H_{37}O^-$	269.284

- **Plastic storage boxes for optical components.**
- **Some boxes exhibited a haze.**
- **Some components stored in those boxes also exhibited small amounts of haze.**
- **Was haze from the storage boxes volatilizing to contaminate the components?**
- **SIMS analysis of both hazed boxes and hazed components gave identical organic fractionation patterns.**
- **Fractionation patterns identified the haze as distearyl thiodipropionate.**
- **Cleaning methods developed to prevent that compound from forming on the plastic boxes.**

X-RAY PHOTOELECTRON SPECTROSCOPY (XPS)

ELECTRON SPECTROSCOPY FOR CHEMICAL ANALYSIS (ESCA)

- **Solid sample surface bombarded with X-rays.**
- **X-rays eject electrons from the sample surface.**
- **Binding energy of the electrons (X-ray energy – kinetic energy of the electrons) provides chemical identification of substrate elements.**
- **Oxidation state information (element valence, as positive or negative ions) is also identified.**
- **Electrons only escape from surface or near-sirface regions of the sample.**
- **Spatial resolution ≈5-10 um.**

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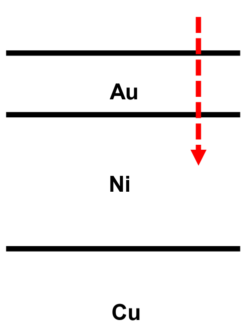
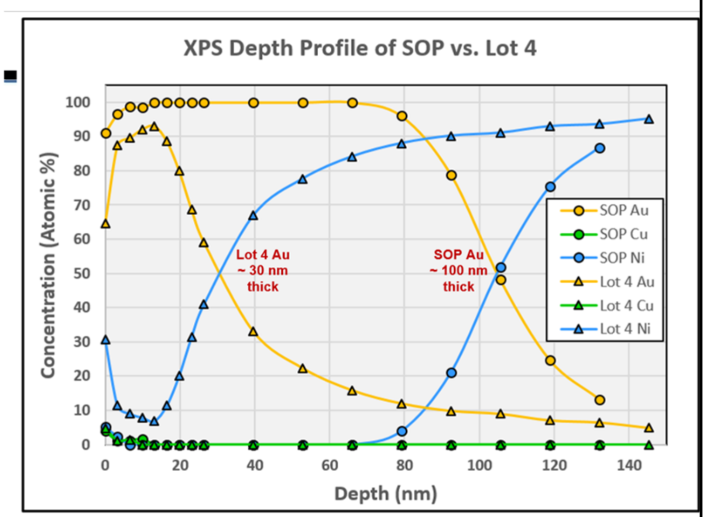
X-RAY PHOTOELECTRON SPECTROSCOPY





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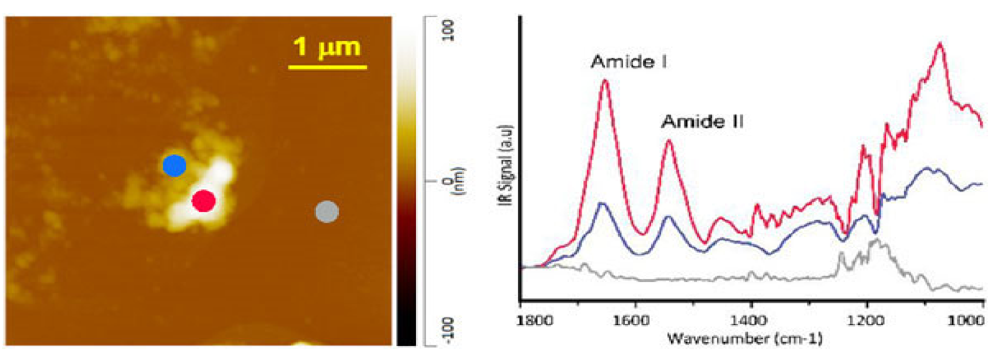
MICRO FOURIER TRANSFORM INFRARED SPECTROPHOTOMETRY (FT-IR)

- **Broad frequency range of infrared light impinges on surface of interest.**
- **Reflected IR light is collected in a spectrometer and plotted by wavelength vs reflected peak intensity.**
- **FT-IR wavelength range is typically 2.5-16um, or 4000-600cm^{-1}.**
- **Wavelengths of peak locations identify functional structure of organic molecular species.**
- **Usually used to identify residual molecular contamination.**
- **The method is also used in transmission mode for analysis of organic chemical compounds.**

FT-IR

Microcontamination on partially patterned silicon wafers.



The blue and red peak envelopes near 1650cm^{-1} and 1520cm^{-1} clearly identify the contamination as residuals of mono-substituted amide-containing chemical compounds […CO-NH-C_xH_y…], traced to incompletely removed photolithographic material.

COMPARISON OF METHODS

Properties	EDS	Auger	SIMS	XPS	FT-IR
Excitation source	Electron beam	Electron beam	Ion beam	X-rays	Infrared light
Type of information	Elemental	Elemental	Elemental, Molecular	Elemental; Valence state	Molecular
Spatial resolution	≈100Å	≈70Å	0.3-0.5um	≈5-10 um	≈2mm
Surface/depth resolution	1-5um	Uppermost ≈20Å	Uppermost ≈50Å	Uppermost ≈25Å	≈1-10 mm
Elemental sensitivity	≈0.1%	≈0.1%	Ppm-ppt range	≈0.1%	Ppm range

MORE METHODS

- **Thermogravimetric Analysis (TGA); weight change.**
- **Thermomechanical analysis (TMA); CTE.**
- **Atomic Force Microscopy (AFM); surface physics, imaging**
- **X-ray Fluorescence Spectrometry (XRF); elemental analysis**
- **Contact Angle Goniometry; surface cleanliness/contamination**
- **Ion Chromatography (IC); ionic contaminant identification**

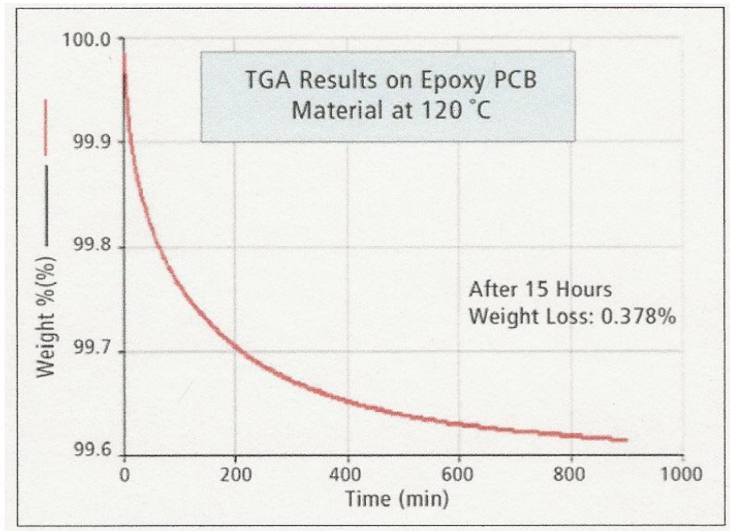
THERMOGRAVIMETRIC ANALYSIS

- **Materials weight loss or gain as function of temperature.**
- **Especially applicable to polymeric or organic materials used in component construction or assembly.**
- **Can be use in materials qualification studies**

TGA APPLICATIONS

- **Moisture Content**
- **Decomposition temperatures**
- **Rate of degradation**
- **Oxidative stability**
- **Thermal stability**
- **Volatile Organic Compounds (VOC) analysis**
- **Analysis of evolved gases using TGA/FTIR**
- **Effects of reactive atmospheres on materials**
- **Determination of inert filler or ash contents**

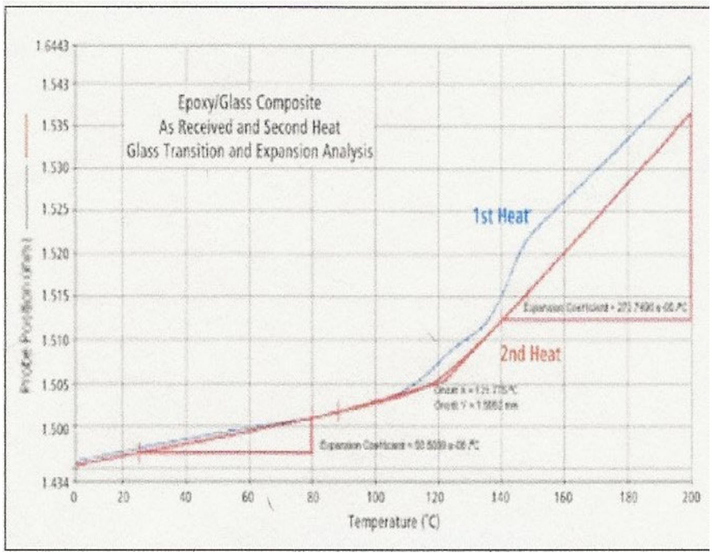
TGA SCAN – EPOXY PCB



THERMOMECHANICAL ANALYSIS

- **Measures dimensional properties of material**
  - **Expansion**
  - **Penetration**
  - **Coefficients thermal expansion (CTE)**
- **Ensures that individual component materials, which need to fit intimately, expand and contract similarly with temperature.**
  - **Mold compounds**
  - **Adhesives**
  - **Conformal coatings, etc.**

TMA SCAN – PCB MATERIAL



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LIST OF FA LABS

- **HI-REL (http://www.hrlabs.com/index.php?id=main.php)**
- **Riga Labs (http://www.rigalab.com)**
- **Evans Analytical Group EAG (http://www.eag.com/mte/)**
- **SEM Lab, Inc. (http://www.semlab.com)**
- **Oneida Research Services (http://www.orslabs.com/about.php)**
- **ITT/Excelis Ft. Wayne (http://www.exelisinc.com/solutions/Product-Assurance-Laboratory/Pages/default.asp**
- **Raytheon https://www.reliabilityanalysislab.com/Homepage.asp**

Where to get more info on FA?

- ISTFA
  http://www.asminternational.org/web/istfa-2015
- EEE International Reliability Physics Symposium (IRPS)
- Electronic Device Failure Analysis Society
  http://www.asminternational.org/web/edfas
- GIDEP (Government-Industry Data Exchange Program)

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Summary

- Package related failures are a part of life… hopefully minimized and detected before shipment to customer
- Careful FA investigation and root cause analysis will drive corrective actions and minimize field failures
- Questions?????

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ASSISTANCE WITH ELECTRONIC MATERIALS ANALYSES, STUDIES, OR INVESTIGATIONS

T J Green Associates is always available to help design materials analysis studies, to select the right method(s) to apply, to select commercial analytical lab services with the capability to perform analyses, and to interpret, explain and report analytical results.

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Thank You!

Thomas J Green
TJ Green Associates LLC
739 Redfern Lane
Bethlehem PA 18017
Email: tgreen@tjgreenllc.com
Website: www.tjgreenllc.com
Phone: 610-625-2158

"A Veteran Owned Small Business"

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