Surviving the Heat Wave

A Presentation on Thermally Induced Failures and Reliability Risks Created by Advancements in Electronics Technologies...and How Modeling Early in the Design Process Can Identify These Issues

June 10, 2020 NCCAVS Presentation





ARINC 429-Mil-Std-1553 Module



Enphase/Solarbridge Micro-Inverter



Thermo-Electric Module



Cobham-Carson Sikorsky Suite



IGBT



Voltage Power Modules





What Do They All Have in Common?

- High Temperature Environments
- Vibration and Shock Environments
- Temperature and Power Cycling Environments
- High Current Flows and Thermal Transfer Requirements
- A variety of materials forming the product



Failure Mechanisms

- Thermo-mechanical fatigue induced failures
 - CTE mismatch
 - Temperature swings
- Bond Wire Fatigue
 - Shear Stresses between bond pad and wire
 - Repeated flexure of the wire
 - Lift off (fast temperature cycling effect)
 - Heel Cracking
- Die Attach Fatigue
- Solder Fatigue
 - Voids
- Device Burn Out



Why Do Electronics Fail Under Thermal Cycling?

- A. We use lots of different materials
 - Semiconductors, Ceramics, Metals, Polymers



- B. We bond these different materials together
 - Plating, Solder, Adhesive



• C. These materials expand/contract at different rates



Why Do Electronics Fail Under Thermal Cycling?

- Two different expansion/contraction behaviors
 - Because solder is connecting two materials that are expanding / contracting at different rates (GLOBAL)
 - Because solder is expanding / contracting at a different rate than the material to which it is connected (LOCAL)
- This differential expansion and contraction introduces stress into the solder joint
 - This stress causes the solder to deform (aka, elastic and plastic strain)
- The extent of this strain (that is, strain range or strain energy) tells us the lifetime of the solder joint
 - The higher the strain, the more the solder joint is damaged, the shorter the lifetime





Drivers for Solder Joint Thermo-Mechanical Failures

• Knowing the critical drivers for solder joint fatigue, we can develop predictive models and design rules







• Wire bonding has been the most common interconnect for IC packages for over 50 years. The most common materials are gold, aluminum, and more recently copper. The most common bond pad material is aluminum.



• Wire bonds tend to fail if exposed to elevated temperatures (intermetallic formation), exposure to elevated temperature and humidity (corrosion) and exposure to temperature cycling (low cycle fatigue).



Stacked Die Configuration

- Die stacking technologies have been demonstrated to > 9 high stacks
 - Most stack ups are limited to 4 die
 - Driven by test, yield and logistic limitations
- Stacked die packaging comes in three flavors
 - All driven by need to provide ledges for wire bonding
- Pyramid or 'cake' configuration
 - Smaller die are placed on larger die
- Stacking traps heat (higher junction temperatures)
 - Increase in upset events, shorter lifetimes









- Elimination of leaded devices
 - Provides lower RC and higher package densities
 - Reduces compliance



Solder Wearout

- Design change: More silicon, less plastic
- Increases mismatch in coefficient of thermal expansion (CTE)
- Hotter devices due to increases change in temperature (ΔT)



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Solder Phase Coarsening

- There are two fundamental forces that drive grains in polycrystalline materials to grow. Grains coarsen because grain boundaries are areas of high potential energy. This is the primary driving force in single-phase materials. During grain coarsening, as grains grow larger, the total grain boundary area decreases, which, in turn lowers the free energy of the system.
- Particles with smaller size tend to combine into a larger particle one with lower total interfacial energy. Grain growth is driven by the local boundary curvature and the presence of triple junctions, which remain in equilibrium and act as anchors to grain boundary mobility. Grain boundary mobility is highly dependent upon grain orientations across the boundary.



Solder Phase Coarsening

• From the original solder joint (left) the grains will grow as the solder joint is stressed. The growing grains will cause micro-voids to appear on the grain boundaries. The micro-voids will connect with each other to create micro-cracks and eventually macro-cracks. If the load is distributed evenly across the joint this will happen everywhere at the same time. In BGA balls this will happen in an entire layer of the bulk solder. If the load is not even then the grain growth and micro cracks are formed in the stress concentration and the micro-crack is advancing along a crack path.





Solder Joint Coarsening Due to Thermal Stresses





Printed Circuit Board Analysis – Glass Style

• PCB laminates (and prepregs) are fabricated with a variety of glass styles



- Problem: Most datasheet properties are for laminate with 7628 glass style
 - Most laminate (and prepreg) in complex PCBs have a low volume fraction of glass (i.e., 1080 or 106)

Glass Style	Resin Volume Content	Fiber Volume Content
1027	0.86	0.14
1037	0.86	0.14
106	0.84	0.16
1067	0.84	0.16
1035	0.83	0.17
1078	0.82	0.18
1080	0.79	0.21
2313	0.74	0.26
2116	0.71	0.29
3313	0.71	0.29
3070	0.68	0.32
1647	0.66	0.34
1651	0.66	0.34
2165	0.66	0.34
2157	0.66	0.34
7628	0.64	0.36



Printed Circuit Board Analysis – Effect of Glass Style

- Realistic target for board CTE is between 15 and 17 ppm/°C
- Most laminate suppliers provide CTExy values

	370HR				
	Typical Value				
Glass Transition Tempera	180				
Decomposition Temperat	340				
T260 Deg C (TMA)	60				
T288 Deg C (TMA)	30				
CTE 7 avia	A. Pre-Tg	45			
CTE, Z-axis	B. Post-Tg	230			
CTE X. Yaxes	A. Pre-Tg	13/14			
01E, X-, 1-4xc3	B. Post-Tg	14/17			

- Key concern, these values are typically for a low resin content laminate (46%-50% resin content by weight, 7628 glass style)
- However the most popular laminates have much higher resin contents
 - Higher resin content = higher CTE
 - Lower modulus



Plated Through Hole Fatigue

- PTH fatigue is the circumferential cracking of the copper plating that forms the PTH wall
- It is driven by differential expansion between the copper plating (~17 ppm) and the out-of-plane CTE of the printed board (~70 ppm)
- Validated industry failure model available IPC-TR-579
- When a PCB experiences thermal cycling the expansion/contraction in the z-direction is much higher than that in the x-y plane. The glass fibers constrain the board in the x-y plane but not through the thickness. As a result, a great deal of stress can be built up in the copper via barrels resulting in eventual cracking near the center of the barrel as shown in the cross section photos below.







- Near the glass transition temperature (Tg), CTE changes more rapidly than modulus
 - Changes in the CTE in polymers tend to be driven by changes in the free volume
 - Changes in modulus tend to be driven by increases in translational / rotational movement of the polymer chains
- Increases in CTE tend to initiate before decreases in modulus because lower levels of energy (temperature) are required to increase free volume compared to increases in movement along the polymer chains
 High stresses generated due to CTE increase before



Polymer Science and Technology, Chapter 4: Thermal Transitions in Polymers, Robert Oboigbaotor Ebewele, CRC Press, 2000





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Reliability Physics Modeling – Fastest Way to Analyze

- Data Transition to Sherlock
 - How can we model the PWB, parts, interconnect materials, stresses in the products lifetime and reliability metrics, utilizing reliability physics.
 - Import GERBER or ODB++ files for the PWB layout
 - Import a csv delimited BOM for the parts list data
 - Load the mechanical and thermo-mechanical stresses the product will encounter
 - Load the reliability requirements for life expectancy,







Import Electronic Design Files (GERBER/ODB++/IPC-2581)





Sherl	ock	Lamin	ate Lib	orary	[T				State State		
Manufacturer Doosan	Material	Product Name	CTExy (ppm/C)	CTEz (ppm/C)	Exy (M	Sherlock Part	Library	arch criter						
minates (45 of	406)						matching parts. You r selected manufacture	may leave er.	Sho	rlook	Dooko	ao Libro	n/	
Manufacturer	Material	Product Name	CTExy (ppm/C)	CTEz (ppm/C)	Exy ()		Library:	Global Part	Sile	HUCK	гаска	ye Libia	I Y	
Doosan	CEM-1	DS-7106	20	90	3400						The Court	Ring (mark)	Destant Name	lane as
Doosan	CEM.1	DS-7106 (HC)	13	90	3400		Use AVL: N	10	Package	ype	Pin Count	Size (mm)	Package Name	Image
Doosan	CEMA	DE 7406A	20	90 90	2400		Use Wizard: N	10	POFP	ALL	1	ALL	GFN-4 (19X17)	-
Doosan	CEM-1	DS-7100A	20	20	3400		Manufacturer:	11	OF J		1	1.0 x 1.0	OFN-4 (MO-220VEEB)	
Deesse	CEM-J	05-1203	20	55	3400		Dard Humbers		OFP/LOFP			14×18	QFN-6 (MO-252UAAD)	JAN WELL
Joosan	CEM-J	US-7209 (HC)	20	50	3400		Part Number: 7		RADIAL	8		1.4x20	QFN-6 (MO-252WAAD)	
Joosan	CEM-3	US-7209 (P)	18	55	3400		Criteria: P	refix Match	SIP	10		1.5 x 1.0	QFN-6 (MO-287UAAF)	
Doosan	CEM-3	DS-7209A	20	55	3400				SM / SMA / SMB /	SMC 12		1.5 x 1.5	QFN-6 (MO-287UFAD)	
Doosan	CEM-3	DS-7209A (G)	20	55	3400		ListPart	3	SOD	14		1.5x2.0	QFN-6 (MO-287X1AAF)	
Doosan	FR-1	DS-1107	90	90	2000				SOIC	16	5	1.6x1.2	QFN-6 (MO-287X1FAD)	
Doosan	FR-1	DS-1108	90	90	2000	Filters			Dackages (515.	4 3384)	hand	and the second s		hand
Doosan	FR-2	DS-1202	90	90	2000	-	Ondlinether	Out	Packages()	- 3384)				
Doosan	FR-2	DS-1202G	90	90	2000	Manufacturer	Part Number	Partiy	Type	Pin Count	Size (mm)	Package Name	Package Material	Package Leads
Doosan	FR-4	DS-5000	18	75	23426			_	QFN	48	8.0 x 8.0 x 1.0	QFN-48 (MO-229VLLD)	OVERMOLD-QFN	48 - Leadless - COPPER
Doosan	FR-4	DS-7209 (ST)	15	55	23426	Search Results (1000)			QFN	48	9.0 x 9.0 x 0.5	QFN-48 (MO-248XMMC)	OVERMOLD-QFN	48 - Leadless - COPPER
Doosan	FR.4	05.7402	15	30	24804	Search Results (1000)			QFN	48	9.0 x 9.0 x 0.6	QFN-48 (MO-248UMMC)	OVERMOLD-QFN	48 - Leadless - COPPER
Doosan	ED.4	DS-7402 (H)	44	30	26182	Manufacturer A	Part Number	Part Ty	OFN	48	90×90×08	QFN-48 (MO-220VMMC)	OVERMOLD-OFN	48 - Leadless - COPPER
Deessa	50.4	DE 7402 (ET)		50	22420	CTS RESISTOR PRODUCTS	73U3108N	RE SIST	OFN	48	9.0 x 9.0 x 0.0	OFN-48 (MO-250VMMC)	OVERMOLD-QFN	48 - Leadless - COPPER
boosan	FR-4	05-7402 (51)	10	00	23420	CTS RESISTOR PRODUCTS	73U3109N	RE SIST	QFN	48	12.0 x 12.0 x 2.1	QFN-48 (MO-251AGG8)	OVERMOLD-QFN	48 - Leadless - COPPER
Joosan	FR-4	DS-7402 BS (DF)	17	70	24804	CTS RESISTOR PRODUCTS	741C083153JP	RESIST	QFN	52	6.0 x 6.0 x 0.4	QFN-52 (MO-265A)	OVERMOLD-QFN	52 - Leadless - COPPER
Doosan	FR-4	DS-7402H(GP)	16	65	26182	CTS RESISTOR PRODUCTS	741C083220JP	RESIST	QFN	52	8.0 x 8.0 x 0.8	QFN-52 (MO-220WLLD-1)	OVERMOLD-QFN	52 - Leadless - COPPER
Doosan	FR-4	DS-7405	18	55	23426	FAIRCHILD/ON SEMICONDUCTOR	74LCX078QX	IC	QFN	52	8.0 x 0.8 x 0.8	QFN-52 (MO-220WLLD-4)	OVERMOLD-QFN	52 - Leadless - COPPER
Doosan	FR-4	DS-7405 (ST)	18	55	23426	FAIRCHILD SEMI LTD	74AC138SC	IC	QFN	52	8.0 x 8.0 x 1.0	QFN-52 (MO-220VLLD-1)	OVERMOLD-QFN	52 - Leadless - COPPER
Doosan	FR-4	DS-7405A	18	55	23426	FAIRCHILD SEMICONDUCTOR	74HCT32MX	IC	QFN	52	8.0 x 8.0 x 1.0	QFN-52 (MO-220VLLD-4)	OVERMOLD-QFN	52 - Leadless - COPPER
Doosan	FR-4	DS-7405MM	18	55	23426	FAIRCHILD SEMICONDUCTOR	74LCX07MTC	IC	QFN	52	10.0 x 10.0 x 0.8	QFN-52 (MO-250VNNC)	OVERMOLD-QFN	52 - Leadless - COPPER
Doosan	FR-4	DS-74055	18	55	23426	HARRIS	74HCT140		CEN .	52	12.0 x 12.0 x 2.1	GFN-52 (MO-251AGG8-1)	OVERMOLD-QFN	52 - Leadless - COPPER
Doosan	FR-4	DS-7408	15	55	23426	IOT	74CBTLV3245PGG	IC	OFN	54	50×50×05	OFN-56 (MO-245WLLD)	OVERMOLD-QFN	56 - Leadless - COPPER
7405.0000	1000	1	1.00	1	1	IDT. INTEGRATED DEVICE TECHNOLOGY INC	72V205L15PEGI	IC I	OFN	56	8.0 x 8.0 x 0.8	QFN-56 (MO-220WLLD-5)	OVERMOLD-OFN	56 - Leadless - COPPER
				-		IDT. INTEGRATED DEVICE TECHNOLOGY INC	74CBTLV3125PGC8	IC	QFN	56	8.0 x 8.0 x 0.8	QFN-56 (MO-220WLLD-6)	OVERMOLD-QFN	55 - Leadless - COPPER
Customize					IDT. INTEGRATED DEVICE TECHNOLOGY INC	74CBTLV3126PW-0100	IC.	QFN	56	8.0 x 8.0 x 0.8	QFN-56 (MO-250VLLD)	OVERMOLD-QFN	56 - Leadless - COPPER	
					NEXPEDIA	74AHCT574PW 118	IC.	QFN	56	8.0 x 0.8 x 0.8	QFN-56 (MO-243VLLD)	OVERMOLD-QFN	56 - Leadless - COPPER	
						NEXTERNA	74AUP2C00CM	IC IC	QFN	56	8.0 x 8.0 x 1.0	QFN-56 (MO-220VLLD-6)	OVERMOLD-QFN	56 - Leadless - COPPER
						NEVDEDIA	74AUP2C00CM 125	in and a second	QFN	56	8.0 x 8.0 x 1.0	QFN-56 (MO-220VLLD-5)	OVERMOLD-QFN	56 - Leadless - COPPER
						A	1900F2000000,125	~	QFN	56	8.0 x 8.0 x 1.0	QFN-56 (MO-220VLLD-2)	OVERMOLD-QFN	56 - Leadless - COPPER
						1			QFN	56	8.0 x 8.0 x 1.0	QFN-56 (MO-208MMEA)	OVERMOLD-QFN	56 - Leadless - COPPER
								-	QFN	56	8.0 x 8.0 x 1.0	QFN-56 (MO-208MMEA-H)	OVERMOLD-QFN	56 - Leadless - COPPER
									CEN	2.2	0.0.00.000	OEN 66 (MO 3200/88880 21	CIVEDRACI & CEN	LE Intelars CODDED



Life Cycle Conditions



DOD O L II



Virtual Power Cycling

• You can override the isothermal temperatures in the event editor by uploading component temperatures, or thermal maps (analysis or IR camera).









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Geometries, Properties, Conditions, Loads







- Stacked Vs. Staggered
 - Mosaic mesh
 - Trace modeling





Von Mises Stress















Example: Effects of Vibration

- Board Bending
 - Components can shake off due to fatigue in leads or solder



- Component Resonance
 - Lead and solder fatigue due to component motion









Simulation of Mitigation Strategy





Creating a Model for BGA Packages

• Sherlock can export a detailed mesh for all the layers of the BGA











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- Modeling today's complex electronics using simulation tools is a cost-effective way to assess the reliability of a design prior to committing to manufacturing.
- Electronics, due to the myriad of materials implemented in the component packages, interconnects and circuit board make failure isolation and identification very difficult.
- Assessing the potential effects of failures early in the design process allows the designer to implement adjustments to obviate these failure issues.



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