Minimizing Thermo-Mechanical Stress in Chipscale eGaN Devices

Enhancement-mode gallium nitride (eGaN) FETs have demonstrated excellent thermo-mechanical reliability in actual operation in the field or when tested according to AEC or JEDEC standards. This is because of the inherent simplicity of the "package," the lack of wire bonds, dissimilar materials, or mold compound [1].

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In addition to the component-level reliability, there are other industry specific standards like IPC-9592, or OEM environmental requirements that impose system or board-level tests for components mounted on a PCB. Among these, there is always a subset that induces severe thermo-mechanical stress on surface-mounted parts such as eGaN FETs, and especially on the solder joints between the parts and the board. For instance, the most stringent temperature cycling requirement (Class II Category 2) from the IPC-9592 standard calls for 700 cycles at −40°C to 125°C without failure in a sample size of 30 units. The reliability of the solder attachments depends on several factors that are independent of the device, including the PCB layout, design and material, the assembly process, the heatsinking solution in operation, and the nature of the application. Therefore, providing a precise model to predict time to failure in a particular application becomes infeasible and impractical. Nevertheless, in the past, EPC published a model to predict time to failure of solder joints based on the correlation between strain energy density and fatigue lifetime [2,3]. In this article, more Temperature Cycling, and Intermittent Operating Life (also known as Power Temperature Cycling) results will be presented under different conditions. In addition, data and analysis on how to improve solder joint reliability with the use of underfill materials will be provided. Underfills are commonly used in applications that may expose surface mount devices to the harshest environmental conditions. It is important to emphasize that underfill is not required to ensure proper operation of eGaN FETs. In fact, EPC conducts most of the reliability tests during product qualification with the devices under test mounted on FR4 boards with no underfill. The list of tests includes HTRB, HTGB, H3TRB, uHAST, MSL1, IOL, HTOL, ELFR, HTS and in many cases TC. That being said, underfill may be used for improved board-level reliability since it reduces the stress on the solder joints resulting from coefficient of thermal expansion (CTE) mismatches between the die and PCB. Moreover, underfill provides pollution protection and additional electrical isolation in those cases with strict creepage and clearance requirements. Finally, underfill also helps in reducing the junction-to-board thermal impedance since the materials used have higher thermal conductivity than air, although lower than typical thermal interface materials. Note that the incorrect choice of an underfill material could also worsen solder joint reliability. Therefore, guidelines based on simulation and experimental results will be provided.

Criteria for Choosing a Suitable Underfill

The selection of underfill material should consider a few key properties of the material as well as the die and solder interconnections. Firstly, the glass transition temperature of the underfill material should be higher than the maximum operating temperature in application. Also, the CTE of the underfill needs to be as close as possible to that of the solder since both will need to expand/contract at the same rate to avoid additional tensile/compressive stress in the solder joints. As a reference, typical lead-free SAC305 and Sn63/ Pb37 have CTEs of approximately 23 ppm/°C. Note that when operating above the glass transition temperature (Tg), the CTE increases drastically. Besides Tg, and CTE, the Young Modulus – a gauge of material "stiffness" - is also important. A very stiff underfill can help reduce the shear stress in the solder bump, but it increases the stress at the corner of the device, as will be shown later in this section. Low viscosity (to improve underfill flow under the die) and high thermal conductivity are also desirable properties. Table 1 compares the key material properties of the underfills tested in this study.

Underfill Study under Temperature Cycling

Temperature Cycling (TC) results of various eGaN FETs under two different conditions, with and without the underfill materials listed earlier will now be explored. Two temperature cycle ranges were tested: (i) −40°C to 125°C; and (ii) −55°C to 150°C. For all cases, the parts were mounted on DUT cards or coupons consisting of a 2-layer, 1.6 mm thick, FR4 board. SAC305 solder paste and water-soluble

Manufacturer	Part Number	Tg (TMA)	CTE (ppm/C) Below Tg	CTE (ppm/C) Above Tg	Storage Modulus (DMA) @25°C (N/mm²)	Viscosity @25°C	Poisson's Ratio	Volume Resistivity	Thermal Conductivity	Dielectric Strength
HENKELS LOCTITE	ECCOBOND UF 1173	160	26	103	6000	7.5 Pa*S				
NAMICS	U8437-2	137	32	*100*	8500	40 Pa*S	0.33	>1E15 Ω-cm	0.67 W/mK	
NAMCIS	XS8410-406	138	19	*70*	13000	30 Pa*S				
MASTERBOND	EP3UF	70	25-30	75-120	3400	10-40 Pa*S	0.3	>1E14 Ω-cm	1.4 W/mK	450 V/mil
AI TECHNOLOGY	MC7885-UF	236	20		7500	10 Pa*S		>1E14 Ω-cm	1 W/mK	750 V/mil
AI TECHNOLOGY	MC7885-UFS	175	25		7500	10 Pa*S		>1E14 Ω-cm	2 W/mK	1000 V/mil

Table 1: Underfill Material Properties

flux was used, followed by a flux clean process prior to the underfill. Temperature Cycling data for EPC2001C and EPC2053 are provided in Tables 2 through 5 and results for EPC2206 are provided in the Weibull plot in Figure 1. For both temperature ranges, the Namics underfills (U8437-2_N and 8410-406B) provide a large lifetime advantage compared to no underfill. The same applies to the Henkels (UF1137_H). On the other hand, Masterbond EP3UF was found to degrade the reliability. It is thought that this was primarily the result of the low Tg, which meant that the underfill was exercised well beyond its glass transition temperature in all our studies. However, based on material properties, it is suspected that Masterbond EP3UF may be a suitable candidate for applications staying below 70°C.

Product/DOE		EPC2701C									
Stress condition: -40°C to 125°C	Status	300 cycles	550 cycles	850 cycles	1000 cycles	1250 cycles	1550 cycles	1750 cycles	1950 cycles	2150 cycles	2450 cycles
No Underfill	Completed	0/32 fail	0/32 fail	0/32 fail	0/32 fail	2/32 fails	5/32 fails	8/32 fails	15/32 fails	20/32 fails	26/32 fails
	On-going	0/32 fail	0/32 fail	0/32 fail	0/32 fail						
Henkels UF1137_H	On-going	0/40 fail	0/40 fail	0/40 fail	0/40 fail	0/40 fail					
Masterbond EP3UF_M	On-going	0/40 fail	0/40 fail	14/40 fails	31/40 fails						
MC7685-UFS	Completed	0/32 fail	0/32 fail	0/32 fail	0/32 fail	1/32 fails	2/32 fails	2/32 fails	3/32 fails	6/32 fails	14/32 fails
MC7885-UF	Completed	0/32 fail	0/32 fail	0/32 fail	0/32 fail	0/32 fail	0/32 fail	0/32 fail	0/32 fail	1/32 fails	4/32 fails
Namics 8410-406B	Completed	0/32 fail	0/32 fail	0/32 fail	0/32 fail	0/32 fail	0/32 fail	0/32 fail	0/32 fail	0/32 fail	0/32 fail
Namics U8437-2_N	Completed	0/32 fail	0/32 fail	0/32 fail	0/32 fail	0/32 fail	0/32 fail	0/32 fail	0/32 fail	0/32 fail	0/32 fail
	On-going	0/80 fail	0/80 fail	0/80 fail	0/80 fail	0/80 fail					

Table 2: -40°C to 125°C Temperature Cycling results for EPC2001C

Product/DOE		EPC2053									
Stress condition: -40°C to 125°C	Status	300 cycles	550 cycles	850 cycles	1000 cycles	1250 cycles	1550 cycles	1750 cycles	1950 cycles	2150 cycles	2450 cycles
No Underfill	Completed	0/32 fail	0/32 fail	0/32 fail	0/32 fail	0/32 fail	0/32 fail	2/32 fails	3/32 fails	3/32 fails	3/32 fails
Henkels UF1137_H	On-going	0/40 fail	0/40 fail	0/40 fail	0/40 fail	0/40 fail					
Masterbond EP3UF_M	On-going	1/40 fails	7/40 fails	15/40 fails	25/40 fails	39/40 fails					
MC7685-UFS	Completed	0/32 fail	0/32 fail	0/32 fail	1/32 fails	17/32 fails	32/32 fails	32/32 fails			
MC7885-UF	Completed	0/32 fail	0/32 fail	0/32 fail	0/32 fail	0/32 fail	0/32 fail	0/32 fail	1/32 fails	1/32 fails	1/32 fails
Namics 8410-406B	Completed	0/32 fail	0/32 fail	0/32 fail	0/32 fail	0/32 fail	0/32 fail	0/32 fail	0/32 fail	0/32 fail	0/32 fail
Namics U8437-2_N	Completed	0/32 fail	0/32 fail	0/32 fail	0/32 fail	0/32 fail	0/32 fail	0/32 fail	0/32 fail	0/32 fail	0/32 fail
	On-going	0/40 fail	0/40 fail	0/40 fail	0/40 fail	0/40 fail					

Table 3: -40°C to 125°C Temperature Cycling results for EPC2053

Product/DOE		EPC2701C				
Stress condition: -55°C to 150°C	Status	300 cycles	600 cycles	900 cycles	1100 cycles	1300 cycles
No Underfill	Completed	0/16 fail	0/16 fail	1/16 fails	1/16 fails	2/16 fails
Henkels UF1137_H	On-going	0/20 fail	0/20 fail	0/20 fail	1/20 fails	
Masterbond EP3UF_M	On-going	0/20 fail	0/20 fail	4/20 fails	6/20 fails	
MC7685-UFS	Completed	0/16 fail	0/16 fail	0/16 fail	1/16 fails	1/16 fails
MC7885-UF	Completed	0/16 fail	0/16 fail	0/16 fail	0/16 fail	0/16 fail
Namics 8410-406B	Completed	0/16 fail	0/16 fail	0/16 fail	0/16 fail	0/16 fail
Namics U8437-2_N	Completed	0/16 fail	0/16 fail	0/16 fail	0/16 fail	0/16 fail
	On-going	0/20 fail	0/20 fail	0/20 fail	0/20 fail	

Table 4: -55°C to 150°C Temperature Cycling results for EPC2001C

Product/DOE		EPC2053				
Stress condition: -55°C to 150°C	Status	300 cycles	600 cycles	900 cycles	1100 cycles	1300 cycles
No Underfill	Completed	0/16 fail	0/16 fail	0/16 fail	0/16 fail	1/16 fails
Henkels UF1137_H	On-going	0/20 fail	0/20 fail	0/20 fail	0/20 fail	
Masterbond EP3UF_M	On-going	5/20 fails	15/20 fails			
MC7685-UFS	Completed	1/16 fails	9/16 fails	13/16 fails		
MC7885-UF	Completed	2/16 fails	1/16 fails	7/16 fails		
Namics 8410-406B	Completed	0/16 fail	0/16 fail	0/16 fail	0/16 fail	0/16 fail
Namics U8437-2_N	Completed	0/16 fail	0/16 fail	0/16 fail	0/16 fail	0/16 fail

Table 5: -55°C to 150°C Temperature Cycling results for EPC2053

Intermittent Operating Life Study

In Temperature Cycling, both the device and PCB are placed inside a chamber that cycles the ambient temperature, leading to an isothermal temperature change across the assembly. In Intermittent Operating Life (IOL), temperature rise is realized by dissipating power inside the device. Therefore, in IOL only the device and the PCB in the vicinity of the die change in temperature. As a result, the stresses on the solder joints resulting from the CTE mismatch between the eGaN FETs and PCB are not as high as in Temperature Cycling. However, the time to complete a full cycle is much faster than in TC (Note that IOL may also be known as Power Temperature Cycling). Figure 2 shows the results of a group of 32 samples of EPC2206 tested to failure under two different conditions. In all cases, each cycle consisted of a heating period of 30 seconds, followed by a cooling period of another 30 seconds. In Figure 2, information in blue shows the devices that were cycled between 40°C and 100°C, and in orange, the devices cycled between 40°C and 150°C. In both cases, solder fatigue is the only failure mechanism, so the slopes of the Weibull fits were almost the same. However, the Mean Time to Failure was strongly accelerated by the ΔT and Tmax reached during each cycle.

In addition, a third cohort of parts using underfill Namics U8437-2 was started cycling between 40°C and 150°C.

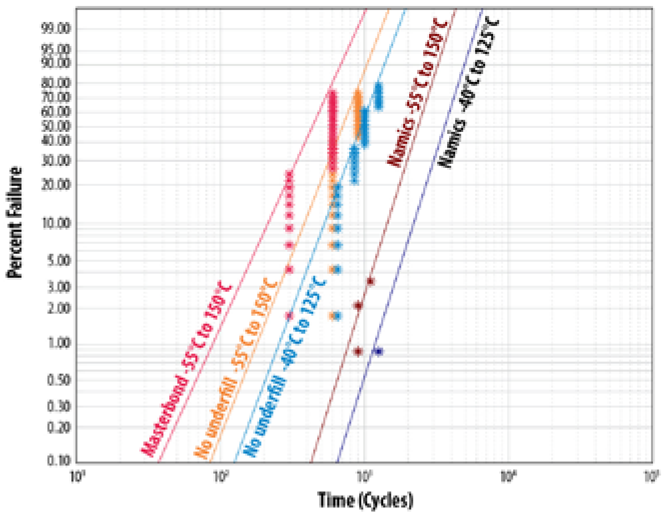

Figure 1: Weibull plots of Temperature Cycling results of EPC2206

After 53,000 cycles no failures were observed. The green line in Figure 2 assumes one failure after 53,001 cycles, and therefore can be viewed as a lower bound on the performance of this underfill. Clearly, as was found in the TC studies, the Namics underfill was found to affect a significant improvement (> 100x) in lifetime under cyclic temperature stress.

Finite Element Analysis

To better understand the key factors influencing thermo-mechanical reliability when using underfills, finite element simulations of EPC2206 under temperature cycling stress were conducted. Figure 3 shows the simulation deck used for this analysis. The die is placed on a 1.6 mm FR4 PCB, and the temperature change is ΔT = +100°C above the neutral (stress free) state. Two key underfill parameters were varied: Young's modulus and CTE. As shown in the figure, stress is analyzed along the cut line shown, providing visibility into the stress within the solder bars, die, and underfill.

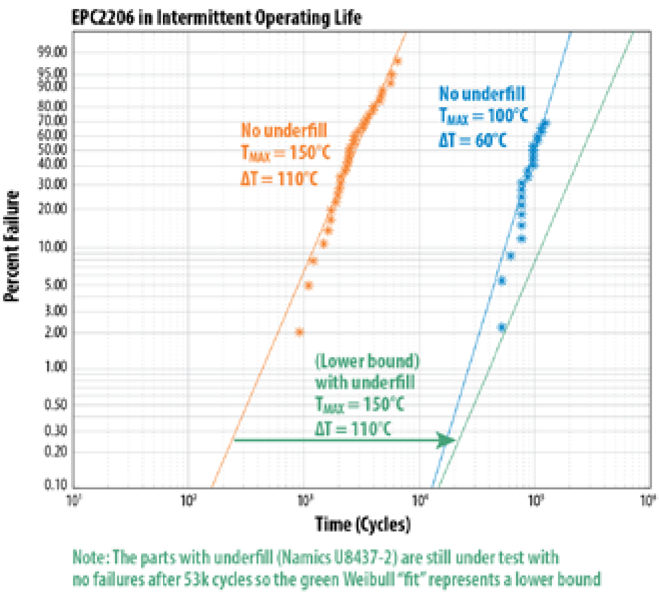

Figure 2: Weibull plots of Intermittent Operating Life results of EPC2206

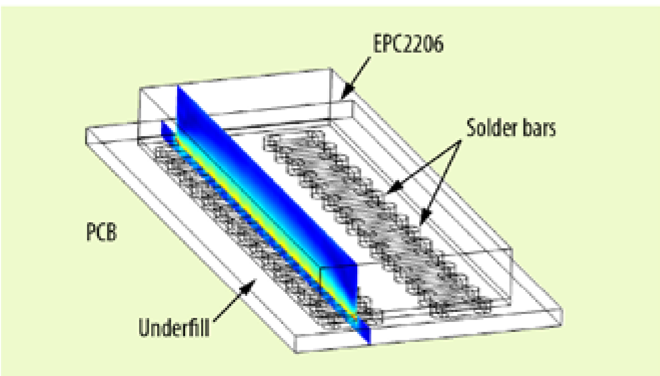

Figure 3: Simulation deck for finite element analysis of stresses inside EPC2206 under temperature cycling stress. Die with underfill mounted on a 1.6 mm FR4 PCB. Stress is analyzed along the cut line shown.

Figure 4 shows the Von Mises [4], or peak shear stress, in the edge-most solder bar along the cutline. For clarity, only stress in the solder bar is shown. In addition, mechanical deformations are exaggerated by 20 times in order to illustrate the shear displacement in the joint. Four distinct underfill conditions are simulated by changing the Young's modulus (E) or the CTE of the underfill. As can be seen, the solder bar in the no underfill case has by far the most extreme shear stress and deformation. The addition of underfill significantly alleviates stress from the joint, with the higher the E, the less stress in the joint. For underfills with poor CTE matching to the solder joint, stresses can also build up in the joint.

Figure 5 shows the same four conditions, but this time the Von Mises stress is shown in the die and underfill as well. As can be seen, the high Young's modulus cases show low stress in the solder joint, but high stress inside the die and underfill near the die edge. These high stresses can lead to cracking and ultimate failure inside the device. FEA analysis shows that there is an optimal Young's modulus in the range of ~6 to 13 GPa, providing a good compromise between protecting the solder joint and protecting the die edge. With regard to CTE, the analysis shows that high underfill CTE (> 32) should be avoided.

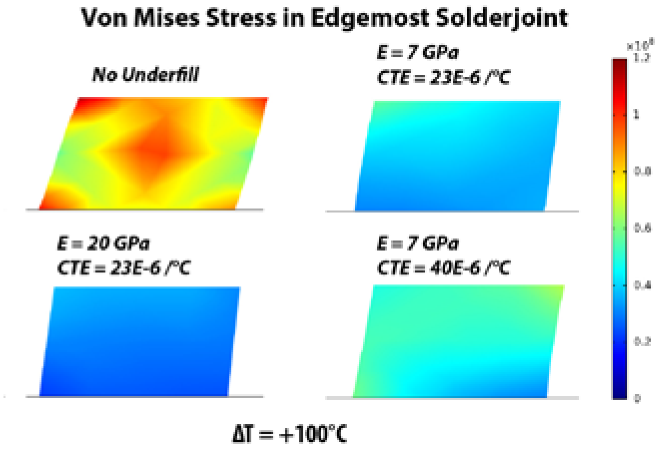

Figure 4: Von Mises (peak shear stress) in the edge-most solder bar under a temperature cycle change of ΔT = +100C. Four different underfill conditions are simulated, with changing Youngs modulus (E) of the underfill, and different CTE as well. Note that mechanical deformation has been exaggerated by 20x in all cases.

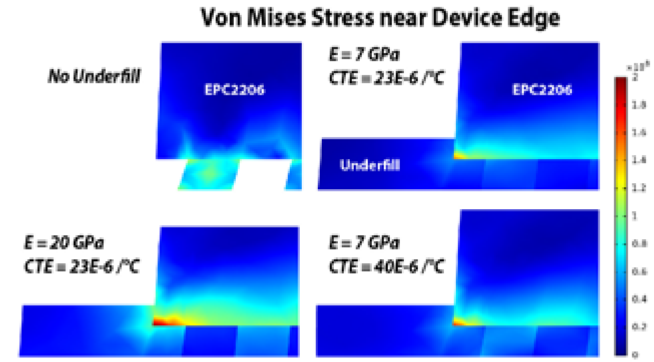

Figure 5: Von Mises (peak shear stress) in the edge-most solder bar under a temperature cycle change of ΔT = +100C. Four different underfill conditions are simulated, with changing Youngs modulus (E) of the underfill and different CTE as well. Note that deformation has been exaggerated by the same scale in each picture.

Guidelines for Choosing Underfill

The main guidelines for choosing an underfill for use with eGaN FETs are listed below:

- Underfill CTE should be in the range of 16 to 32 ppm/°C, centered around the CTE of the solder joint (24 ppm/°C). Lower values within this range are preferred because they provide better matching to the die and PCB.
- Glass transition temperature (Tg) should be comfortably above the maximum operating temperature. When operated above Tg, the underfill loses its stiffness and increases its CTE, which may compromise solder joint reliability.

- Young's (or Storage) modulus in the range of 6−13 GPa. If the modulus is too low, the underfill is compliant and does not relieve stress from the solder joints. If it is too high, the high stresses begin to concentrate at the die edges. From the experimental results in this study, Henkels UF1137_H and Namics 8410-406B and U8437-2_N underfills provide excellent boost in thermomechanical reliability when used with eGaN FETs.

References:

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