The Significance of Glass Transition Temperature of Molding Compounds for Screening and Reliability Qualification of COTS PEMs

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Abstract

Reliability evaluation and screening of COTS PEMs for military and aerospace applications necessitates stress testing of the parts at highest allowable temperatures. The transition of epoxy molding compounds from a glassy to rubbery state drastically changes thermal, mechanical, and electrical characteristics of molding compounds and conceivably might introduce new failure mechanisms thus limiting the maximum stress temperatures. In this work molding compounds in different plastic encapsulated devices have been characterized using a thermo-mechanical analyzer. The results of Tg measurements are compared with the rated temperatures of the parts and results of burn-in, temperature cycling, high temperature storage, and highly accelerated humidity stress testing. Experiments performed in this work and analysis of literature data have revealed no evidence that exceeding Tg during standard screening and qualification testing causes failures in normal quality lots of PEMs.

Key words: glass transition temperature, PEM, reliability.

1. Introduction

The benefits of using advanced technology and high performance COTS (commercial off-the shelf) PEMs (plastic encapsulated microcircuits) have come to the community of military and aerospace equipment manufacturers along with the burden of evaluating and qualifying the devices to the level required for high reliability applications. In many cases a PEM is intended for use within a relatively low range of temperatures specified by the manufacturer. However, to assure quality of the parts, the users of COTS PEMs are employing screening and qualification procedures according to the military and JEDEC standards, which require high temperature stress testing. Table 1 shows major elements and typical conditions of commonly accepted screening and qualification procedures.

One of the major problems of implementing these procedures is the fact that PEMs are typically rated for much lower temperatures compared to military grade parts encapsulated in hermetic ceramic or metal packages. There are several parameters, which are specified by manufacturers and commonly considered as limits for stress testing of PEMs. These parameters include maximum junction temperature (T_{jmax}, normally 150 °C), maximum storage temperature (T_{st}, normally 150 °C), and maximum operational temperature (T_{op}, normally 85 °C).

Detailed discussion of the significance of the manufacturer specified parameters is out of the scope of this paper. Nevertheless, it is important to mention that there are no standard procedures, which would allow estimation of these limiting characteristics, so it is quite possible that in many cases they are just marketing parameters [1] used by manufacturers to ensure the competitiveness of their product rather than any reliability-related characteristics of PEMs.

Table1. Typical tests performed during screening and qualification of PEMs for high reliability applications.

TEST	Standard (typical conditions)
Burn-in (BI)	MIL-STD-883, TM 1015 (125 °C/160 hrs)
High Temperature Operational Life (HTOL)	MIL-STD-883, TM 1005 (125 °C/1000 hrs)
Temperature Cycling (TC)	MIL-STD-883 TM 1010 (-65 °C to +150 °C).
Highly Accelerated Temperature and Humidity Stress Test (HAST)	JESD22 - A110/118 (130 °C, 85% RH, 96 hrs)
High Temperature Storage Life (HTSL)	JESD22-A103B (150 °C/1000 hrs).

Another factor, which might possibly limit the temperature during stress testing, is the transition of molding compounds from a glassy to a rubbery state, which occurs at a temperature called the glass transition temperature (Tg). When a temperature of a die is close to or exceeds Tg of a molding compound

(MC), electrical and mechanical properties of the encapsulant might change significantly and new degradation mechanisms may cause failures of the part. For multifunctional epoxy and orthocresol novolac epoxy molding compounds, Tg values are in the range from 150 to 190 °C, which exceeds in most cases the stress test temperatures. However, for low mechanical stress biphenyl epoxy MCs Tg values can be as low as ~120 °C. Besides, power devices can operate at temperatures up to 175 °C, which might be above the Tg even for relatively high-Tg encapsulating materials. Process variations in manufacturing of MCs and/or insufficient curing after molding of PEMs might result in a 10 to 25 °C decrease of Tg compared to the nominal values [2]. This indicates that in many cases a PEM may be tested at temperatures exceeding Tg of MC, and it is therefore quite possible in the case of failures that the validity of such a test would be questionable.

This work analyzes the significance of Tg as a limiting factor for qualification and screening of PEMs for high reliability applications. For this purpose Tg values in various COTS PEMs have been measured and the obtained values have been correlated with the manufacturers' data and results of screening and reliability qualification testing. Effects of a glassy or rubbery state of MC on possible degradation mechanisms in PEMs during different high temperature stress testing are considered.

2. Experiment

The glass transition temperature of epoxy molding compounds was measured directly on PEMs using a thermal mechanical analyzer, TMA2940, manufactured by TA instruments. Our experiments have shown that the best reproducibility of results is achieved when testing is performed at a rate of 3 ^{o}C/min during cooling from 220 ^{o}C followed by heating of the part in the analyzer at the same rate. This allows for monitoring and controlling of the moisture desorption and stress relief effects in plastic packages and assures elimination of possible errors related to the presence of moisture and built-in mechanical stresses. Warpage of PEMs might result in erroneous measurements of Tg and CTE and is especially significant for the parts with high aspect ratio (thickness 0.8 to 1.5 mm and a length of more than 3 to 6 mm). Measurements on small pieces cut from the package avoid warpage-related errors.

3. High temperature bias testing (BI and HTOL)

3.1. Possible mechanism of Tg effect.

Increasing temperature above Tg releases segmental movement in polymer chains and enhances electrical polarization. According to the model of ionic dissociation in polymers, increasing the dielectric constant exponentially increases the concentration of mobile charges generated by dissociation of ionic impurities. Excessive concentration of ions is commonly expected to accelerate degradation of PEMs by the charge instability mechanisms.

3.2. Comparison of Tg with manufacturers' data.

The glass transition temperatures have been measured in 35 plastic parts manufactured by four different companies. Results of these measurements were compared with the manufacturer's specified temperatures: T_{jmax}, T_{st}, and T_{op} (see Figure 1). A significant proportion of the parts (~43%) had Tg below the T_{jmax} and T_{st}, and 14% had Tg below T_{op}. Note, that MCs in all power devices (5 out of 35 parts), which are normally operating at high temperatures, had Tg below the rated operational and storage temperatures. This indicates that manufacturers do not have much concern regarding Tg of the molding compounds used.

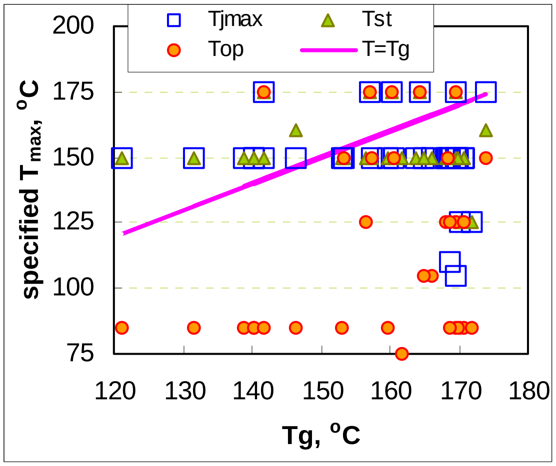

Figure 1. Relationship between Tg of molding compounds and maximum temperatures specified by PEM manufacturers. No correlation was found.

Burn-in screening of 31 part types performed at GSFC at temperatures varying from 85 to 150 °C during 160 to 330 hours also did not show any correlation between Tg and the proportion of BI failures.

3.3. BI testing of power devices.

It has been reported [3, 4] that the characteristics of MCs used for high voltage MOSFETs affect reliability during high temperature testing. Degradation of electrical characteristics of the parts was observed after High Temperature Reverse Bias (HTRB) testing and was explained by positive mobile ions [3] and specific of the molding compound-die interfacial chemistry [4]. Note, that the effect of MC was observed during testing at relatively low temperatures of 125 ^{o}C and 150 ^{o}C, which were below Tg of the encapsulating materials used.

To evaluate the possible effect of temperatures exceeding Tg on stability of high voltage devices, HEXFET parts encapsulated in MC with Tg = 167 ^{o}C were tested at ambient temperatures of 150 and 175 ^{o}C for 168 hours; first at VG=10 V and VDSS=0 (gate stress test), and then at VG=0V, VDSS=180 V (HTRB test). The parts had no failures and manifested only minor variations in the mobile-charge-sensitive parameters (VTH and BVDS). These results agree with the manufacturer's reliability reports, according to which no failures occurred in similar devices during 1000 hours of HTOL testing.

Two types of PEMs encapsulated in SOIC8 and SOIC16 packages were found to use MCs with Tg < 135 ^{o}C. According to the manufacturer's data, HTOL testing of these parts were successfully performed at 135 ^{o}C.

These results indicate that BI and HTOL mostly accelerate die-related degradation processes and normally no direct effect of characteristics of MC and Tg in particular on stability of devices is observed. For HTB testing the risk of insufficient stress on PEMs by limiting the temperature to Tg is far greater than a conceivable risk of introducing new failure mechanisms. MCs with excessive ionic contamination might affect reliability of PEMs even below Tg. In this case a possibly high failure rate during testing at T>Tg would have helped to reveal poor quality lots of PEMs.

4. Highly Accelerated Temperature and Humidity Stress Test (HAST)

4.1 Possible mechanism of Tg effect.

Moisturizing of MC plasticizes the polymer matrix, decreases Tg, and increases its dielectric constant. This can intensify charge instability failures at T > Tg for the same reasons considered above. Another Tg-related degradation mechanism is due to compression caused by the shrinkage of encapsulant. These forces prevent water needed for corrosion, from accumulating at the bond pad surface [5]. As mechanical stresses build up with increasing Tg, the humidity performance of PEMs should also improve. However, this model failed to account for the possibility of delamination due to moisture-induced swelling and for the decrease in Tg due to moisturizing of MC.

4.2. Effect of HAST on Tg.

Thermo-mechanical analysis of eleven different PEMs was performed before and after HAST testing. The results of these measurements are shown in Figure 2. An average decrease in Tg was ~15 ^{o}C, however for different part types it varied from 5 to 30 ^{o}C. Similar to what was observed in [6] there is no correlation between the initial Tg values and the degree of Tg decrease after moisturizing.

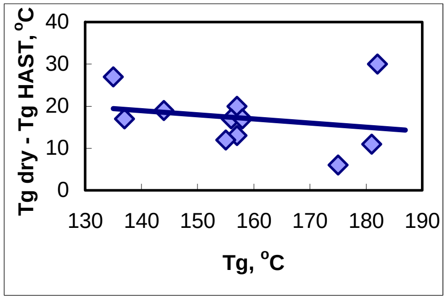

Figure 2. Relationship between the initial Tg and the HAST-induced decrease of Tg showing poor correlation.

4.3. HAST test results.

HAST testing was performed at 130 ^{o}C/85% RH for 250 hours under bias conditions on 30 samples of each of the 24 different part types. Failures were observed in 12 out of 24 part types and varied for the failed lots from 1.1% to 100%. The results showed no correlation between Tg and the proportion of HAST failures.

4.4. Analysis of HAST failures.

Acoustic microscopy of most of the HAST failures revealed excessive delaminations at the die surface and/or lead-to-MC interfaces, which might have contributed to corrosion of aluminum metallization observed on some of the failed parts.

Due to a fast relaxation of mechanical stresses in polymers at T≈Tg, it is commonly assumed that dice in plastic packages do not experience significant mechanical stress at temperatures close to Tg. In humid conditions mechanical stresses in PEMs at the die/MC interface are a sum of compressive stresses caused by mismatch of the coefficients of thermal expansion (CTE) between MC (α_{MC}) and die (α_{Si}), and tensile stresses developed by moisture-induced swelling. The following equation gives an estimation of these stresses at a temperature T:

$$\sigma \propto E \times \left[(\alpha_{MC} - \alpha_{Si}) \times (Tg - T) - CME \times \delta\right],$$

where E is the Young's modulus, CME is the coefficient of moisture expansion, δ is the moisture sorption.

When T > Tg, the value of σ is negative, which indicates the presence of tensile stresses at the die-MC interface and, respectively, a high probability of delamination. The above equation shows that even at T < Tg, delaminations still might form if MC has large CME and δ. For a typical case of CME = 0.2, δ = 0.4%, α_{MC} - α_{Si}=11 ppm/^{o}C, and Tg = 150 ^{o}C, the 'safe' temperature of humidity testing, which would not create delaminations, is approximately 85 ^{o}C.

Considering possible decrease in Tg in humid environments, this means that a significant margin between Tg and the temperature of HAST testing should exist to avoid delamination at the die/MC interface.

5. High temperature storage life (HTSL)

5.1. Possible mechanism of Tg effect.

The generally accepted mechanism of gold/aluminum wire bond degradation at high temperatures [7, 8] involves the following steps: 1) release of chemically active molecules (typically Cl, Br or Sb_20_3) by thermal decomposition from the flame retardant additives in MC; 2) diffusion of the molecules; and 3) chemical reaction with the Al/Au intermetallic (dry corrosion). If diffusion is the limiting stage of this process, then exceeding Tg might accelerate transport of the corrosive molecules to the wire bond intermetallic and thus enhance the rate of degradation. However, no data on the significance of the expected changes in the diffusivity of polymers at T>Tg was found in the literature.

Gallo [7] found that moisture significantly accelerates wire bond degradation and high Tg compounds performed better during HTSL testing compared to low Tg parts. The accelerating effect of moisture and low Tg were both attributed to increasing transport of corrosive ions. Uno and Tatsumi [8] found that the lifetime to bond failure for a biphenyl epoxy MC was shorter than that for a cresol novolac epoxy. The activation energy of wire bond failures for the cresol novolac MC was 2.3 eV in the range from 160 to 200 ^{o}C. The biphenyl epoxy MC had a higher failure rate and lower activation energies: E = 2eV at $150<T<177^{o}$C and 1.5 eV at higher temperatures. This change in the activation energy of degradation occurred at a temperature approximately 50 ^{o}C higher than Tg.

R. Biddle has reported on HTLS experiments performed on PEMs encapsulated in a biphenyl epoxy MC. The activation energy of the wire bond degradation was found to be 0.91 eV at $T<185\ ^{o}$C and, contrary to the results of Udo and Tatsumi [8], increased at higher temperatures. Assuming that Tg of the used MC was in the range from 120 to 140 ^{o}C, the change of the activation energy in these experiments also occurred 45 to 65 ^{o}C above Tg. These data do not support the hypothesis that diffusion of the corrosive molecules, which is controlled by Tg, is the limiting factor of the wire bond degradation.

Sometimes Tg is considered as an indicator of thermal stability of MC and materials with higher Tg are believed to have better long-term high temperature performance. In general this is not true. It is pertinent to note here that the most thermally stable polymers used in electronics, silicone rubbers and Teflon have extremely low Tg of -20 to –120 ^{o}C for the rubbers and –90 ^{o}C for Teflon.

5.2. HTSL test results.

Three different types of PEMs have been stored at temperatures above Tg of the used MCs for up to 6300 hrs. Results of electrical measurements during this test are shown in Table 2. No wire bond related failures were observed in the memory PEMs (PEM1/2). Most failures that did occur were due to data losses in some memory cells. Operational amplifiers (PEM3) had no failures after 1000 hrs at 175 ^{o}C, whereas multiple failures were observed during the storage at 200 and 225 ^{o}C.

Table 2. High temperature storage test (failed/total).

PN (Tg)	T_{st} ^{o}C	Time, hrs					
		24	100	250	500	1000	6300
PEM1 (135 ^{o}C)	150	-	-	0/5	0/5	0/5[1]	0/5[1]
	175	-	-	0/5	0/5[1]	0/5[1]	0/5[1]
PEM2 (135 ^{o}C)	150	-	-	0/8	0/8	0/8	-
	175	-	-	0/8	0/8	0/8	-
	200	-	-	0/8	0/8[1]	-	-
PEM3 (164 ^{o}C)	175	-	0/30	0/30	0/30	0/30	-
	200	0/30	2/30	9/30	16/30	27/30	-
	225	2/30	6/30	18/30	27/30	-	-

[1] memory cell failures.

Failure analysis of the parts after 6300 hrs testing at 150 and 175 ^{o}C showed Kirkendall voiding in the wire bonds above Au/Al intermetallic, but apparently the degradation was not significant enough to cause catastrophic failures of the parts. Most of the PEM3 failures at 200 and 225 ^{o}C were most likely due to increased wire bond contact resistance.

Figure 3 shows that long-term high temperature aging results in approximately 15 ^{o}C increase of Tg, which was independent on the temperature and duration of aging and on the initial value of Tg. This might be due to additional cross-linking in polymer chains and indicates that the thermal stability of MCs does not depend on Tg.

6. Temperature cycling.

6.1. Possible mechanism of Tg effect.

One of the first studies of gold bonding wire failures in PEMs caused by temperature/power cycling [9] revealed excessive grain growth and intergranular fractures, which were accelerated by tensile stresses in the wire. The stresses were due to a significant mismatch in CTE between gold and the MC. At temperatures below Tg the wire is under compressive stresses, which should prevent this type of failures. However, when temperature exceeds Tg, the CTE increases significantly and, what is more important, tensile stresses develop causing cycling fatigue failures.

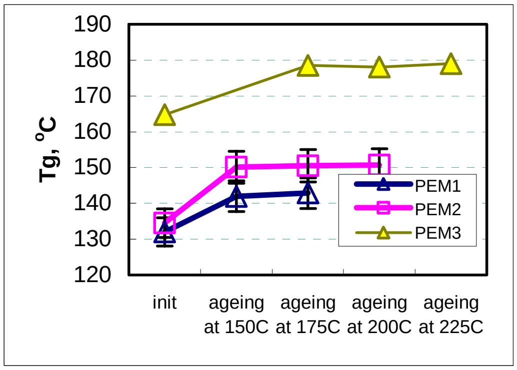

Figure 3. Variations of Tg with aging at different temperatures. Tg values were measured after maximum aging time shown in Table 2.

In contemporary PEMs, fractures of gold wires are not common and most of temperature cycling (TC) failures are due to passivation stress cracking [10, 11] and damage to metallization, especially at the die corners [12], and to wire ball bond rupture associated with MC/die interfacial delaminations [11].

Results of TC of PEMs in PLCC packages encapsulated in six different MCs [10] indicated that the formulation of MC and thermal excursion conditions govern the rate of electrical failures. The rate of failures correlated with the stress index (product of the Young modulus and CTE), but did not show any Tg dependence.

Cory [11] revealed that the results of TC depend not only on the temperature swing, which is commonly used as a major acceleration factor, but also on the absolute temperature of the excursions. Cycling of ASIC PEMs encapsulated in PQFP packages with a MC having Tg of ~160 °C resulted mostly in stress cracking failures when the parts were cycled between –65 and +150 °C, whereas failures during cycling between –55 and +125 °C were due to delamination-induced ball bond lifting. The 50% fail point was ~ 200 cycles in the first case and ~2000 cycles in the second case. In a separate set of experiments two groups of 84-pin PLCC microcircuits were cycled with the same temperature swing of 215 °C: between –65 and +150 °C and between –75 and +140 °C. After 1000 cycles more than 50% of the parts failed in the first group due to stress cracking, whereas parts in the second group started failing by the same mechanism only after 1000 cycles. Although all experiments in this work were performed at temperatures below Tg, the author suggested that the effect of absolute temperature is related to Tg of the used MCs. Note also, that the effect of absolute temperature was observed on the lots known for their crack propensity. When a better quality product in the same MC was tested, no difference in testing in the low and high-temperature range conditions was observed up to 2000 cycles.

6.2. TC test results.

To evaluate the effect of Tg on the results of temperature cycling, several types of PEMs have been subjected to testing at different conditions: TC1=1000 cycles at -55 to +125 °C; TC2=1000 cycles at -65 to +150 °C; TC3= 300 cycles at 0 to +180 °C; TC4=300 cycles at +20 to +200 °C. Tests TC1, TC3, and TC4 had the same temperature swing of 180 °C, but different maximum temperatures, which surpassed the Tg values on 30 to 65 °C. Results of the test are shown in Table 4 and suggest that even significant exceeding Tg does not necessarily cause failures.

Table 4. Results of temperature cycling (failed/total).

PN	Tg, °C	TC1	TC2	TC3	TC4
PEM4	171	0/30	0/16	0/30	1/15*
PEM5	138	-	0/16	0/16	-
PEM3	165	0/30	-	0/30	0/15
PEM6	168	0/30	-	0/30	0/15
PEM7	169	0/30	-	0/30	0/15
PEM8	170	0/30	-	0/30	0/15
PEM1	135	-	0/5	-	-
PEM2	135	-	0/20	-	-
PEM9	153	0/30	-	0/30	0/15
PEM10	163	0/30	-	0/30	1/15*
PEM11	167	0/30	-	0/30	0/15

*failures were not related to wire bond lifting or stress cracking.

7. Summary.

Increasing temperature above Tg changes the rate of temperature variation of most of the characteristics of MCs. This means that whenever the effect of the used MC on reliability of PEMs is observed, changes in the failure rate and introduction of new failure mechanisms at T>Tg might be expected. This effect is very important to consider for analysis of acceleration factors and development of models predicting long-term reliability of PEMs at normal conditions based on high-temperature stress testing results. However, in order to affect the results of the standard screening and qualification tests shown in Table 1, the acceleration due to exceeding Tg should be significant enough to cause failures during the time of testing. Manufacturer data, literature analysis, and our experiments show that for normal quality lots there is likely to be no immediate danger from exceeding Tg during standard qualification and screening testing.

Most manufacturers perform reliability qualification testing without citing any concerns about

Tg. The same is true regarding JEDEC standards except for JESD22-A103B, which warns of a possible Tg effect, but does not provide any details and does not discuss how significant the concern is.

The analyzed data showed no indications of the possibility of low-Tg related failures or introduction of new failure mechanisms during standard BI and HTOL testing.

Failures due to dry corrosion of wire bonds during testing at 150 ^oC require significantly more than 1000 hours even for low Tg MCs. Using a conservative estimate of the activation energy of 0.9 eV, the standard HTSL testing would be equivalent to 11.7 years of operation at the typical maximum rated temperature for PEMs of 85 ^oC. Note, that the reported changes of the failure rate at T>>Tg might be due to alterations in mechanical stresses developed by MC in the wire bonds rather than to changes in their diffusion characteristics.

Our experiments did not show any correlation between Tg and HAST results. However swelling of MCs and results of failure analysis indicate that the possibility of a Tg effect exists and should be considered during HAST testing. At temperatures close to Tg, the hygroscopic swelling and plastification of MCs might create delaminations and facilitate penetration of impurities to the die surface. Note however, that delaminations do not necessarily cause failures during standard HAST testing and corrosion of aluminum metallization might be not the major failure mechanism in PEMs.

Manufacturer reliability reports and our data show that exceeding Tg during –65 to +150 ^oC TC will most likely not cause failures during up to 1000 cycles. However, development of tensile stresses in gold wires and change of the sign of shearing forces in bonds at T>Tg indicate the possibility of intensive wire bond degradation after multiple high temperature excursions. Because temperature cycling is a resource-consuming test, in order to avoid potential damage to flight parts the maximum temperature of TC should be limited to Tg when this test is performed as a screening procedure to precipitate infant mortality failures in potentially mechanically weak parts.

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