The Impact of Glass Transition Temperature of Molding Compounds on Screening and Reliability Qualification of COTS PEMs

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Transition from a glassy to rubbery state drastically changes thermal, mechanical, electrical, and diffusion characteristics of epoxy molding compounds.

- **Diffusion**: Vieth '91
- **Elastic modulus**: Darveaux et al.'95
- **Heat capacity**: TA Instruments
- **Electrical conductivity**: P. Chen et al. '2000
Tg and CTE might affect the performance and reliability of PEMs at extreme temperatures and change the rate of failures.

High-temperature stress testing is commonly used to screen and qualify COTS PEMs for high-reliability applications.

Exceeding Tg might introduce new failure mechanisms.

Can we screen and qualify PEMs at T > Tg?
Purpose and Outline

Analyze the validity of typical screening and qualification tests at temperatures exceeding Tg of molding compounds.

- **Experiment.**
  - High-Temperature Operational Life (HTOL) and Burn-In (BI) testing.
  - High-Temperature Storage Life (HTSL).
  - Temperature Cycling (TC).
  - Highly Accelerated Stress Testing (HAST).
Typical Screening and Qualification Tests for High-Reliability Applications

<table>
<thead>
<tr>
<th>TEST</th>
<th>BI</th>
<th>HTOL</th>
<th>TC</th>
<th>HAST</th>
<th>HTSL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical condition</td>
<td>125 °C 160 hrs</td>
<td>125 °C 1000 hrs</td>
<td>-65 °C to +150 °C</td>
<td>130 °C, 85% RH, 96 hrs</td>
<td>150 °C 1000 hrs</td>
</tr>
</tbody>
</table>

Typical values of Tg for MCs:
Multifunctional and orthocresol novolac: Tg ~ 150 to 190 °C.
Low mechanical stress biphenyl epoxy: Tg ≲ 120 °C.

It is quite possible that some tests are performed at T>Tg.
Tg Measurements Directly on PEMs

TMA2940

Quartz probe

PEM

Thermocouple

ΔL

Diffusion Change [g/µg]

Temperature (°C)

CTE1

CTE2

ΔL

Diffusion Change [g/µg]

Temperature (°C)

IMAPS’03
At T > Tg, the concentration of mobile charges in MC increases, thus accelerating degradation of PEMs by the charge instability mechanisms.

Ionic conduction model: Charge carriers are ions generated by dissociation of impurities (salt MA):

\[ \text{MA} \leftrightarrow _T \text{M}^+ + \text{A}^- \]

The equilibrium constant:

\[ K = \frac{[\text{M}^-] \times [\text{A}^-]}{[\text{M}^+ \text{A}^-]} = f^2 n_0 \frac{1}{1-f} = K_o \times \exp \left( \frac{U_0}{\varepsilon \times kT} \right) \]

Where \( n_0 \) is the concentration of salt molecules; 
\( f \) is the fractional degree of dissociation;
\( U_0 \) is the energy of ions separation.
BI & HTOL: Comparison of Tg With Manufacturers’ Data

- Tg was measured in 35 parts manufactured by Analog Devices, MAXIM, International Rectifier, and Linear Technology.
- No correlation between Tg and operational temperature (Top), storage temperature (Tst), and/or maximum junction temperature (Tjmax) was found.
- 43% of parts had $T_{j\text{max}} > T_{g}$.

Relationship between Tg of MCs and maximum temperatures specified by manufacturers.

Manufacturers do not have much concern regarding Tg.
**BI & HTOL: Stability of High-Voltage Devices at \( T > T_g \)**

- HEXFET plastic parts with \( T_g = 167 \) °C were tested at 150 and 175 °C for 168 hrs; first at \( V_G = 10 \) V and \( V_DSS = 0 \) (gate stress test), and then at \( V_G = 0 \) V, \( V_DSS = 180 \) V (HTRB test).

- Two parts in SOIC8 and SOIC16 packages had \( T_g < 135 \) °C. HTOL testing of these parts at 135 °C showed no failures.

Exceeding \( T_g \) during BI and HTOL normally does not introduce new failure mechanisms.

**BI testing at 175 °C**

![Bi Testing Graph](image)

No degradation at \( T > T_g \) was observed.

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**IMAPS'03** 9
Au/Al WB degradation limits reliability of PEMs at high temperatures.

Degradation mechanism involves:
- release of chemically active molecules from MC;
- diffusion of the molecules to bonds;
- chemical reaction with the Al/Au intermetallic (dry corrosion).

If diffusion limits the process, then exceeding Tg might accelerate transport of the corrosive molecules.

Several researchers reported on changes in the rate of WB degradation at high T; however, these changes occurred at T>Tg.

- There is no evidence that diffusion of corrosive molecules is the limiting factor of the process.
- D(T) characteristics are not known.
### HTSL: Test Results

High-Temperature Storage Test Results (Failed/Total)

<table>
<thead>
<tr>
<th>PN</th>
<th>$T_{st}$ °C</th>
<th>Time, hrs.</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>FM1608 (135 °C)</td>
<td>150</td>
<td>-</td>
<td>-</td>
<td>0/5</td>
<td>0/5</td>
<td>0/5¹</td>
<td>0/5¹</td>
</tr>
<tr>
<td></td>
<td>175</td>
<td>-</td>
<td>-</td>
<td>0/5</td>
<td>0/5¹</td>
<td>0/5¹</td>
<td>0/5¹</td>
</tr>
<tr>
<td>FM1808 (135 °C)</td>
<td>150</td>
<td>-</td>
<td>-</td>
<td>0/8</td>
<td>0/8</td>
<td>0/8</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>175</td>
<td>-</td>
<td>-</td>
<td>0/8</td>
<td>0/8</td>
<td>0/8</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>-</td>
<td>-</td>
<td>0/8</td>
<td>0/8¹</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>OP283 (164 °C)</td>
<td>175</td>
<td>-</td>
<td>0/30</td>
<td>0/30</td>
<td>0/30</td>
<td>0/30</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>0/30</td>
<td>2/30</td>
<td>9/30</td>
<td>16/30</td>
<td>27/30</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>225</td>
<td>2/30</td>
<td>6/30</td>
<td>18/30</td>
<td>27/30</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

¹ memory cell failures

**Low Tg materials can withstand X1,000 hrs at T>Tg**
HTSL: Failure Analysis

FA of memory IC after 6300 hrs. testing at 150 and 175 °C indicated Kirkendall voiding in the wire bonds above Au/Al intermetallic; however, the degradation was not significant enough to cause failures.

Most of the opamp failures at 200 °C and 225 °C were due to increased wire bond contact resistance.

- Increased Rc is less important for digital IC and can cause failures in linear devices.
- Tg effect is conceivable and might be related to changes in mechanical stresses applied to bonds.
HTSL: Does Thermal Stability of MC Depend on Tg?

TGA measurements of MCs with different Tg showed that materials with Tg ~135 °C had higher stability compared to MC with Tg ~ 175 °C.

The most thermally stable polymers used in electronics, silicone rubbers and Teflon, have extremely low Tg of -20 to -120 °C for the rubbers and -90 °C for Teflon.

Tg is not an indicator of thermal stability of MC.
Most TC failures are due to passivation stress cracking and damage to metallization and to wire ball bond rupture associated with MC/die interfacial delaminations.

Cory ['00] revealed that results of TC depend not only on the temperature swing, but also on the maximum temperature, and explained it by the Tg effect.

However, the effect of $T_{max}$ was observed when MC remained in a glassy state.
**TC: Test Results**

Temperature Cycling Test Results (Failed/Total)

<table>
<thead>
<tr>
<th>Test conditions:</th>
<th>package</th>
<th>Tg, °C</th>
<th>TC1</th>
<th>TC2</th>
<th>TC3</th>
<th>TC4</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC1: 1000 c -55 +125°C;</td>
<td>SOIC8_1</td>
<td>171</td>
<td>0/30</td>
<td>0/16</td>
<td>0/30</td>
<td>1/15*</td>
</tr>
<tr>
<td>TC2: 1000 c -65 +150°C;</td>
<td>SOIC8_2</td>
<td>138</td>
<td>-</td>
<td>0/16</td>
<td>0/16</td>
<td>-</td>
</tr>
<tr>
<td>TC3: 300 c 0 +180°C;</td>
<td>SOIC8_3</td>
<td>165</td>
<td>0/30</td>
<td>-</td>
<td>0/30</td>
<td>0/15</td>
</tr>
<tr>
<td>TC4: 300 c +20 +200°C.</td>
<td>SOIC8_4</td>
<td>168</td>
<td>0/30</td>
<td>-</td>
<td>0/30</td>
<td>0/15</td>
</tr>
<tr>
<td></td>
<td>SOIC8_5</td>
<td>169</td>
<td>0/30</td>
<td>-</td>
<td>0/30</td>
<td>0/15</td>
</tr>
<tr>
<td></td>
<td>SOIC8_6</td>
<td>170</td>
<td>0/30</td>
<td>-</td>
<td>0/30</td>
<td>0/15</td>
</tr>
<tr>
<td></td>
<td>DIP28_1</td>
<td>135</td>
<td>-</td>
<td>0/5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>DIP28_2</td>
<td>135</td>
<td>-</td>
<td>0/20</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>TO220_1</td>
<td>153</td>
<td>0/30</td>
<td>-</td>
<td>0/30</td>
<td>0/15</td>
</tr>
<tr>
<td></td>
<td>TO220_2</td>
<td>163</td>
<td>0/30</td>
<td>-</td>
<td>0/30</td>
<td>1/15*</td>
</tr>
<tr>
<td></td>
<td>TO220_3</td>
<td>167</td>
<td>0/30</td>
<td>-</td>
<td>0/30</td>
<td>0/15</td>
</tr>
</tbody>
</table>

* Parametric changes

Exceeding Tg during TC did not cause failures.
HAST: Possible Effect of Tg

Mechanism I.
Moisture decreases Tg and increases dielectric constant, thus intensifying the charge instability failures.

Mechanism II.
Compression caused by the shrinkage of encapsulant prevents water needed for corrosion from accumulating at the bond pad surface. At T>Tg, the probability of delaminations increases.

Mechanical stresses in the presence of moisture:

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

where E is the Young’s modulus, CME is the coefficient of moisture expansion, and \( \delta \) is the moisture sorption.
HAST: Test Results

Effect of initial Tg on the HAST-induced decrease of Tg

![Graph showing the relationship between Tg, °C and Tg dry - Tg HAST, °C.]

- Average decrease in Tg ~15 °C

Correlation between Tg and HAST failures for different PEMs

![Graph showing the correlation between Tg, °C and HAST failures, %.]

- 24 part types HAST 130 °C/85% RH/250 hrs under bias conditions (each lot 30 samples)

No correlation between initial Tg and the decrease of Tg after HAST, and between Tg and the proportion of HAST failures.
Delaminations in HAST failures are typical and are due to swelling of MC.
The probability of delaminations might depend on Tg.
Delaminations might introduce new failure mechanisms.
Effect of Tg on Failure Modes and Mechanisms

When characteristics of MC affect reliability of PEMs, the Tg effect might be expected. This is important for analysis of acceleration factors and for prediction of long-term reliability based on high-temperature stress testing.

Conceivable Situations

Most probable case: Ts>Tc>Tg
\[ \lambda_q >> \lambda_{\text{exper}} \]

Little likelihood case
\[ Tc \sim Tg \]
\[ \lambda_{Ts} << \lambda(Ts) \]

Parts prone to failures related to MC poor quality lot.
Summary

- Performed experiments did not reveal effect of Tg on results of standard screening and qualification testing.
- Changes in failure rates at T>Tg are conceivable and should be considered for analysis of acceleration factors and prediction of long-term reliability of PEMs based on high-temperature stress testing.
- For a normal quality lot there is no immediate danger in exceeding Tg during standard reliability testing.