Package induced instability in voltage reference microcircuits encapsulated in plastics

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Effect of mechanical stresses on reliability: catastrophic and parametric failures

- Packaging related mechanical stresses is a characteristic feature of PEMs.
- MS are caused by cure shrinkage and CTE mismatch between MC and die assembly materials.
- Typical compressive stresses caused by packaging are 50 MPa to 100 MPa.
- MS result in mechanical damage and parametric shift.

Cracking is a result of concentration of internal and external stresses and is typically developed during TC:
- Cratering;
- Wire bond lifting;
- Cracking in passivation;
- Die cracking.
Why mechanical stresses cause changes in characteristics of linear devices?

Parametric variations are due to changes in the electronic band structure of Si, which causes changes in $E_g$ and $\mu$.

- **Piezo-resistance effect** (caused by $\mu$ variations):
  - Si resistors: can reach 2-3% at 100 MPa, has different signs for n- and p-types, and is larger for p-type;
  - MOSFETS: affects $I_{dsat}$, is larger in n-type with longer channels (>1 um).

- **Piezo-junction effect** – the change in the saturation current of BJT (caused by $E_g$ and $\mu$ variations):
  - results in $V_{BE}$ changes up to 4 mV at 200 MPa, which is especially important for band-gap references;
  - decreases with increasing temperature and is larger for compressive stress than for tensile stress.

Variations in mechanical stresses caused by changes in environmental conditions might cause instability in precision linear devices.
Purpose and Outline

**Purpose:** to evaluate moisture absorption and desorption expansion and shrinkage of MCs and assess its effect on characteristics of precision voltage reference PEMs.

**Outline:**
- Introduction.
- Hygroscopic swelling measurements.
- Swelling characteristics of MCs.
- Environmental effects in Vref PEMs.
- Comparison with external mechanical stresses.
- Conclusions
Moisture induced swelling in MCs and mechanical stresses in PEMs

Coefficient of moisture expansion:
CME = (ΔL/L)/(Δm/M)

Mechanical stress in PEMs:

\[ \sigma \approx A \times E \times [(\alpha_{MC} - \alpha_{LF}) \times \Delta T + CME \times \Delta m/M] \]

At \( \alpha_{MC} \approx \alpha_{LF} \) mechanical stresses are due to only variation of moisture content.

At CME = 0.1 to 0.4, \( \Delta \alpha \sim 10 \text{ ppm/}^\circ\text{C} \), and \( \Delta m/M \sim 0.5\% \), moisture-induced stresses are equivalent to thermal stresses at \( \Delta T \sim 50 - 200 \text{ }^\circ\text{C} \).
Hydrostatic weighting technique

**Benefits of hydrostatic weighting technique:**
simple, accurate, fast, in-situ.

**Necessary equipment:**
- Balance ±0.1 mg;
- Beaker;
- Piece of wire;
- **Liquid.** (low molecular weight perfluoropolyether fluid, 1.77 g/cc, $T_b = 175 \, ^\circ C$)

**Theory of technique**

**Archimedes of Syracuse**
Born: 287 BC in Syracuse, Sicily

\[
V = \frac{P - P_{\text{init}}}{\rho_{\text{liquid}}}
\]

\[
CME = \frac{1}{3} \times \frac{V_{\text{moist}} - V_{\text{init}}}{M_{\text{moist}} - M_{\text{init}}} \times \frac{M_{\text{init}}}{V_{\text{init}}}
\]
Swelling test results

Moisture characteristics of different PEMs after 85 °C/85% RH/168 hrs

<table>
<thead>
<tr>
<th>Part</th>
<th>Package</th>
<th>dM, %</th>
<th>dV, %</th>
<th>CME</th>
</tr>
</thead>
<tbody>
<tr>
<td>HA3-5217A-5</td>
<td>DIP-8</td>
<td>0.29 (0.016)</td>
<td>0.25 (0.074)</td>
<td>0.25</td>
</tr>
<tr>
<td>HA3-5104-5</td>
<td>DIP-14A</td>
<td>0.31 (0.012)</td>
<td>0.53 (0.106)</td>
<td>0.49</td>
</tr>
<tr>
<td>HA3-5330-5</td>
<td>DIP-14B</td>
<td>0.32 (0.002)</td>
<td>0.39 (0.045)</td>
<td>0.36</td>
</tr>
<tr>
<td>FM1808</td>
<td>DIP28</td>
<td>0.18 (0.002)</td>
<td>0.20 (0.015)</td>
<td>0.32</td>
</tr>
<tr>
<td>49C465PQF</td>
<td>QFP144/IDT</td>
<td>0.33 (0.011)</td>
<td>0.27 (0.034)</td>
<td>0.24</td>
</tr>
<tr>
<td>LT1014IS</td>
<td>PLCC32</td>
<td>0.27 (0.013)</td>
<td>0.19 (0.07)</td>
<td>0.18</td>
</tr>
<tr>
<td>H7MG00104B</td>
<td>QFP160</td>
<td>0.28 (0.012)</td>
<td>0.09 (0.02)</td>
<td>0.1</td>
</tr>
<tr>
<td>A1240A - 1</td>
<td>QFP144/Actl</td>
<td>0.32 (0.011)</td>
<td>0.12 (0.023)</td>
<td>0.11</td>
</tr>
<tr>
<td>AD780AR*</td>
<td>SOIC8</td>
<td>0.3</td>
<td>0.24</td>
<td></td>
</tr>
<tr>
<td>AD780BR*</td>
<td>SOIC8</td>
<td>0.28</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>LT1461*</td>
<td>SOIC8</td>
<td>0.22</td>
<td>0.27</td>
<td></td>
</tr>
</tbody>
</table>

* measurements were performed using TGA/TMA technique

• Accuracy of the CME measurements is ~15% for large packages (V ~2.5 cm³) and ~30% for smaller packages (V ~0.75 cm³).
• CME is in the range from 0.1 to 0.49.
Moisture uptake sorption isotherms

Equilibrium moisture uptake at 85 °C

Moisture uptake linearly increases with RH and depend only slightly on temperature

Sorption follows Henry’s law:
\[ dM_\infty = \eta \times P = \eta \times P_s \times f \]

Sorption coefficient:
\[ \eta = \eta_0 \times \exp(\Delta H/kT), \]
\[ \Delta H - \text{heat of moisture solution.} \]

Water pressure:
\[ P_s = P_o \times \exp(-Q/kT) \]
\[ Q - \text{heat of water vaporization.} \]

For MC:
\[ \Delta H \approx Q = 0.42 \text{ eV} \]
Moisture swelling variation with temperature and humidity

Equilibrium moisture volume swelling isotherm at 85 °C

Equilibrium moisture volume swelling at 85% RH

- Swelling isotherms had a sigmoidal shape => CME is not a constant (it also depends on baking conditions).
- Swelling efficiency is higher at low and high humidity.
- At 85%RH and 75 °C < T < 130 °C moisture pressure increases >100 times, however swelling variations are <50%.
## Precision bandgap 2.5 V Vref PEMs

Average characteristics of materials and standard deviations (in brackets)

<table>
<thead>
<tr>
<th>Part (DC)</th>
<th>LF CTE, ppm/°C</th>
<th>MC TG, °C</th>
<th>MC CTE1, ppm/°C</th>
<th>MC CTE2, ppm/°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD780AR (0106)</td>
<td>17.5 (Cu)</td>
<td>171 (4.4)</td>
<td>15.1 (2.3)</td>
<td>89 (12)</td>
</tr>
<tr>
<td>AD780BR (0127)</td>
<td>17.5 (Cu)</td>
<td>173 (5)</td>
<td>16.4 (1)</td>
<td>77 (25)</td>
</tr>
<tr>
<td>LT1461AI (0113)</td>
<td>4.3 (alloy 42)</td>
<td>138 (3)</td>
<td>9.8 (0.5)</td>
<td>65 (4.4)</td>
</tr>
</tbody>
</table>
What level of the output stability is necessary?

Data sheet information:
Long-term stability:
- AD780 ± 20 ppm/1khr;
- LT1461 ± 60 ppm/1khr.

By default, humidity is assumed to be constant.

System resolution requirements:

<table>
<thead>
<tr>
<th>Resolution, bit</th>
<th>1LSB, ppm</th>
<th>dVout, µV</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>3906</td>
<td>9766</td>
</tr>
<tr>
<td>10</td>
<td>977</td>
<td>2441</td>
</tr>
<tr>
<td>12</td>
<td>244</td>
<td>610</td>
</tr>
<tr>
<td>14</td>
<td>61</td>
<td>153</td>
</tr>
<tr>
<td>16</td>
<td>15</td>
<td>38</td>
</tr>
</tbody>
</table>

Voltage references are the biggest source of error in AD/DA systems.
Output voltage moisture sorption isotherm

Effect of humidity on Vout deviation measured at RT during storing at 85 °C for 168 hrs.

A negative shift of ~150 to 300 ppm can be expected in vacuum due to moisture outdiffusion.

A positive shift up to 350 ppm can be expected in high humidity conditions.

Voltage output varies virtually linearly with relative humidity.
Unbiased HAST results

Test conditions: soaking for 168 hr at 85% RH at each temperature

Output deviation with the temperature of HAST testing

- Moisture sorption at RT causes output variation comparable to HAST.
- Temperature increase at 85% RH from 85 °C to 150 °C results in relatively small increase of dVout (from ~250 ppm to ~ 400 ppm) due to relatively small variations in ∆m and swelling.
Kinetics of the output deviation due to moisture release

Variation of Vout with time of storing at 85 °C after soaking at 85 °C/85% RH

Output relaxation is due to moisture release and can be described by a simple diffusion model.

At package thickness $2h = 1.5$ mm; moisture diffusion coefficient,

$$D_{85} = 4 \times 10^{-8} \text{ cm}^2/\text{s}$$

$$\tau_{85} = h^2/D \approx 39 \text{ hr}$$
Effect of temperature

Output voltage deviation with temperature

Low temperature hysteresis

Typically, manufacturers do not specify temperature hysteresis

• LT hysteresis is much larger than HT
• Temperature hysteresis is due to creep of MC.
• Temperature variations are partially caused by mechanical stresses.
Effect of external mechanical stresses

Parts attached to epoxy block

Strain gage

Compressive stresses cause negative output deviation

AD780 Stress effect

LT1461 Stress effect

EMPC June’ 03
The output varies linearly with strain.

Measured GF = \( \frac{dV_o}{V_o} / \frac{dL}{L} \) = 0.1 to 0.14
Estimations of the gage factor

Deformation of the package is less than of the epoxy block

\[
\frac{\delta_1}{\delta_2} = \frac{\frac{\alpha_1}{\alpha_2} \times \frac{h_1}{h_2} \times \frac{E_1}{E_2}}{1} + 1
\]

At \(\alpha_1/\alpha_2 \approx 0.14\) to 0.37; \(h_1/h_2 \approx 0.17\); \(E_1/E_2 \approx 5\) to 20, package deformation is 1.5 to 3 times less than of the epoxy block.

\[=> GF = 0.16\) to 0.43\]
Comparison of calculated and experimental Vout deviations

Calculation of package deformation based on $\Delta m$ and CME

<table>
<thead>
<tr>
<th>Part</th>
<th>$\Delta m$, %</th>
<th>CME</th>
<th>package deformation, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD780</td>
<td>-0.17</td>
<td>0.13</td>
<td>0.22</td>
</tr>
<tr>
<td>LT1461</td>
<td>-0.12</td>
<td>0.1</td>
<td>0.27</td>
</tr>
</tbody>
</table>

Calculation of the output deviation

<table>
<thead>
<tr>
<th>Part</th>
<th>package deformation, %</th>
<th>Calculated GF</th>
<th>Calculated dVout, ppm</th>
<th>Experimental dVout, ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD780</td>
<td>0.066</td>
<td>0.16 - 0.26</td>
<td>104 - 168</td>
<td>270 - 350</td>
</tr>
<tr>
<td>LT1461</td>
<td>0.059</td>
<td>0.23 - 0.43</td>
<td>138 - 251</td>
<td>170 - 300</td>
</tr>
</tbody>
</table>

Considering simplifications and possible measurement errors, the calculated moisture-induced output deviation is in reasonable agreement with the experimental data.
CME can be measured using a simple hydrostatic weighting technique with accuracy of 15 to 30%.

Moisture-induced environmental stresses result in parametric shifts of Vref PEMs, which might cause failures in systems with resolution of >12 bits.

Kinetics of $dV_{out}$ in humid/dry conditions can be estimated based on diffusion characteristics of MCs.

External compressive stresses result in negative shift of $V_{out}$. The estimated gage factor is in the range from 0.16 to 0.43.

Estimations of $V_{out}$ deviations based on moisture uptake, CME, and GF are in reasonable agreement with experimental data.