ENVIRONMENTAL HYSTERESIS IN MOLDING COMPOUNDS AND VOLTAGE REFERENCE MICROCIRCUITS ENCAPSULATED IN PLASTICS

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Abstract

Hygroscopic swelling characteristics of different types of molding compounds and electrical parameters of voltage reference microcircuits encapsulated in plastics were measured after saturation with moisture at 85 ^{o}C and humidity varying from 20% to 90% RH. Sorption of moisture at high humidity conditions and desorption during baking resulted in deformation of molding compounds of approximately –0.035% and +0.028% for baking and moisturizing, respectively. The voltage output deviation at these conditions was ±(100 ppm to 300 ppm), which is large enough to cause failures in signal digitizing systems with resolution of 12 bits and higher. An increase in external mechanical compressive stresses caused linear decrease in the voltage output with a gage factor of 1.1 to 1.4. Estimations of the environmental hysteresis in the microcircuits based on the hygroscopic swelling characteristics of molding compounds and gage factors are in reasonable agreement with the experimental data. A simple model of moisture diffusion in flat plastic packages can be used to explain deviations of the voltage output with time after changes in environmental conditions.

1. Introduction

A characteristic feature of plastic encapsulated microcircuits (PEMs) is mechanical stresses developing in silicon dies after encapsulation. These stresses are due to shrinkage of the epoxy matrix during the curing process and to mismatch of the coefficients of thermal expansion (CTE) between the molding compound and silicon. Excessive mechanical stresses can damage the surface structure of dies causing cratering at the wire bonds, cracking in the glassivation, and/or damage to underlying metallization.

The typical level of compressive stresses caused by packaging is in the range from 50 MPa to 100 MPa [1, 2]. In most cases these stresses will not cause direct mechanical damage to the die; however, they are significant enough to cause parametric shifts in sensitive semiconductor devices. High precision linear devices and, in particular, operational amplifiers and voltage reference microcircuits, are known to be especially sensitive to mechanical stresses created by plastic packaging [3].

The effect of mechanical stresses is due to changes in the electronic band structure of silicon, which alters the energy band gap, Eg, and the mobility of free charge carriers, μ. Both effects are anisotropic and depend on the doping level of the silicon [4]. The effect of mobility variations (piezo-resistance effect) has different signs for n- and p-types of silicon, is larger for p-type resistors than for n-types, and can reach 2 to 3% at stresses of approximately 100 MPa.

Variations of Eg and μ result in changes of the saturation current of p-n junctions in silicon devices (piezo-junction effect) and can cause changes in the base-emitter voltage drop (VBE) of bipolar junction transistors (BJT) up to 4 mV at 200 MPa [4, 5]. This effect is larger for compressive than for tensile stresses, which makes it especially important for PEMs and for the band-gap voltage reference microcircuits in particular. The voltage reference microcircuits are widely used in analog-to-digital or digital-to-analog converters, so errors in the Vref output are considered a major source of errors in such mixed signal systems.

Exposure of PEMs to different environmental conditions results in hygrothermal swelling or shrinkage of molding compounds (MC) due to moisture sorption/desorption processes and due to creep in the epoxy matrix. Variations in the volume of plastic packages might cause with time changes of mechanical stresses in silicon chips, resulting in significant parametric drift and failures of sensitive devices. However, the effects of environmental stresses in MCs and in linear PEMs have not been explored adequately.

Until recently, moisture-induced stresses have been largely ignored in the analysis of packaging stresses. E. H. Wong and co-authors [6] attributed this to lack of characterization techniques, lack of material hygroscopic swelling characteristics, and under-assessment of the magnitude of hygroscopic stresses.

The purpose of this work is to evaluate moisture absorption and desorption expansion and shrinkage of molding compounds and assess its effect on characteristics of precision voltage reference microcircuits encapsulated in plastics.

2. Technique

2.1. Measurements of hygroscopic swelling

The volume hygroscopic expansion coefficient, b_{MC}, is defined as a ratio between moisture swelling ($\delta^v_{MC} = \Delta V_{MC}/V_{MC}$) and moisture uptake ($\delta^m_{MC} = \Delta M_{MC}/M_{MC}$): $b_{MC} = \delta^v_{MC}/\delta^m_{MC}$ and indicates the "efficiency" of the adsorbed moisture to cause swelling of polymers. The coefficient of moisture expansion (CME) is the ratio between the strain and moisture uptake and is one-third of the volume hygroscopic expansion coefficient:

$$CME = \frac{\Delta l / l}{d^m_{MC}} = \frac{1}{3} b_{MC} = \frac{1}{3}\frac{d^v_{MC}}{d^m_{MC}}$$

where l is the initial size of a dry sample of MC and Δl is the change of the size due to moisture sorption.

Several techniques are available for measurement of the hygroscopic swelling characteristics of epoxy composites and molding compounds including direct measurement of dimensions of samples before and after moisturizing, Moire interferometry [7], and combined thermal mechanical analysis (TMA) and thermal gravitational analysis (TGA) measurements performed on two identical samples [6].

In this work, the hygrothermal expansion was calculated based on volume measurements of PEMs using the Archimedes principle. According to this technique, the weight measurements of a plastic package, P, were first performed in air and then after immersion into a fluid, P_{im}. The volume of the sample was calculated using the density of the liquid, ρ_{liquid}:

$$V = \frac{P - P_{im}}{r_{liquid}}$$

To calculate the CME, the volume and mass of a sample were measured two times: after saturation in moisture environments and after baking-out at 125 °C:

$$CME = \frac{1}{3} \times \frac{V_{moist} - V_{bake}}{M_{moist} - M_{bake}} \times \frac{M_{bake}}{V_{bake}}$$

A low molecular weight perflouropolyether (PFPE) liquid was used as media for the immersion measurements. This liquid is chemically inert and has high boiling point (~175 °C), high density at 25 °C (~1.77 g/cm^3), and low vapor pressure (>1 torr). The weight measurements were performed using a digital scale with 0.1 mg accuracy, which gives an error in the volume measurements of 0.1% to 0.04% for the packages with volume ranging from 0.1 cm^3 to 3 cm^3, respectively.

A simple calculation allows for accounting for the presence of lead frames in plastic packages:

$$CME_{MC} = CME_{pac} \frac{1 + V_{LF}/V_{MC}}{1 + \frac{r_{LF}}{r_{MC}}\frac{V_{LF}}{V_{MC}}}$$

Here V_{LF} and ρ_{LF} are the volume and the specific density of the lead frame; V_{MC} and ρ_{MC} are the volume and the specific density of the molding compound.

For a typical case of a QFP144 package with a thickness of 3.4 mm and a copper lead frame of 0.18 mm of thickness, $V_{LF}/V_{MC} \approx 0.036$. Considering that the specific densities of copper and MC are 9 g/cc and 1.8 g/cc, calculations give $CME_{MC} \approx 0.87 \times CME_{pac}$. Experiments showed that the CME calculations based on direct measurements of samples of MCs and of plastic packages (QFP144 type) agree within 5%. The accuracy of moisture swelling measurements was approximately 15% for relatively large packages (~ 2.5 cm^3) and approximately 30% for packages with a smaller volume (~ 0.75 cm^3).

2.2. Measurements of voltage reference microcircuits

Three types of precision bandgap, 2.5 V voltage reference microcircuits manufactured by Analog Devices (AD780AR, AD780BR) and Linear Technology (LT1461AI) have been used in this study. All parts were packaged in SOIC-8 type packages and had a thin layer of silicone gel coating on the dies. However, the parts featured different materials used for the lead frames and molding compounds. Table 1 shows thermo-mechanical characteristics (coefficients of thermal expansion, CTE, and glass transition temperatures, Tg) of the materials used.

Table 1. Average characteristics of materials and standard deviations (in brackets)

PN	LF CTE, ppm/°C	MC Tg, °C	MC CTE1, ppm/°C	MC CTE2, ppm/°C
AD780AR	17.5 (Cu)	171 (4.4)	15.1 (2.3)	89 (12)
AD780BR	17.5 (Cu)	173 (5)	16.4 (1)	77 (25)
LT1461AI	4.3 (A42)	138 (3)	9.8 (05)	65 (4.4)

The parts have high long-term stability of ±20 ppm/1000 hrs for AD780 and ±60 ppm/1000 hrs for LT1461. Note that to successfully operate in a 12-bit resolution A/D or D/A system, the stability of the output should be better than 244 ppm; for the 14-bit and 16-bit systems the required stability is 61 ppm and 15 ppm, respectively. The specified level of stability indicates that the parts could be used successfully in systems with resolution up to 14 bits; however, it is assumed that moisture content in the packages and the environmental conditions (temperature and humidity) during operation are stable.

In this study, characteristics of the parts were measured at room temperature before and after exposure to various environments. The measurements were performed on groups of 5 to 10 devices using a precision semiconductor parameter analyzer hp1456A.

3. Swelling characteristics of molding compounds

Swelling characteristics were measured on several types of plastic packages using three samples for each part type. The parts were measured after baking at 125 ^{o}C/48 hours and then after 1 week of storage at 85 ^{o}C/85% RH conditions. Averaged moisture characteristics of the packages and standard deviations of the moisture uptake and swelling (in brackets) are displayed in Table 2.

Table 2. Moisture characteristics of different PEMs after 85 ^{o}C/85% RH/186 hrs.

Part	Package	dM, %	dV, %	CME
HA3-5217A-5	DIP-8	0.29 (0.016)	0.25 (0.074)	0.25
HA3-5104-5	DIP-14A	0.31 (0.012)	0.53 (0.106)	0.49
HA3-5330-5	DIP-14B	0.32 (0.002)	0.39 (0.045)	0.36
FM1808	DIP28	0.18 (0.002)	0.20 (0.015)	0.32
49C465PQF	QFP144/IDT	0.33 (0.011)	0.27 (0.034)	0.24
LT1014IS	PLCC32	0.27 (0.013)	0.19 (0.07)	0.18
H7MG00104 B	QFP160	0.28 (0.012)	0.09 (0.02)	0.10
A1240A - 1	QFP144/Actl	0.32 (0.011)	0.12 (0.023)	0.11
AD780AR*	SOIC8	0.3		0.24
AD780BR*	SOIC8	0.28		0.22
LT1461*	SOIC8	0.22		0.27

* measurements were performed using TGA/TMA technique.

The results show that the CME values for different molding compounds vary from 0.1 to 0.49, which is in agreement with the results reported in the literature [6-9].

To evaluate the effect of relative humidity on moisture uptake and swelling of molding compounds, several types of PEMs and two types of epoxy molding compounds were subjected to environmental stresses at 85 ^{o}C and relative humidity varying from 20% to 90%. Three samples of each type of package and MCs were stored consequently at humidity of 20%, 40%, 60%, 80%, and 90% for 168 hrs. Masses and volumes of all samples were measured after bake (baseline data) and after each RH run. The results of these experiments are shown in Figure 1.

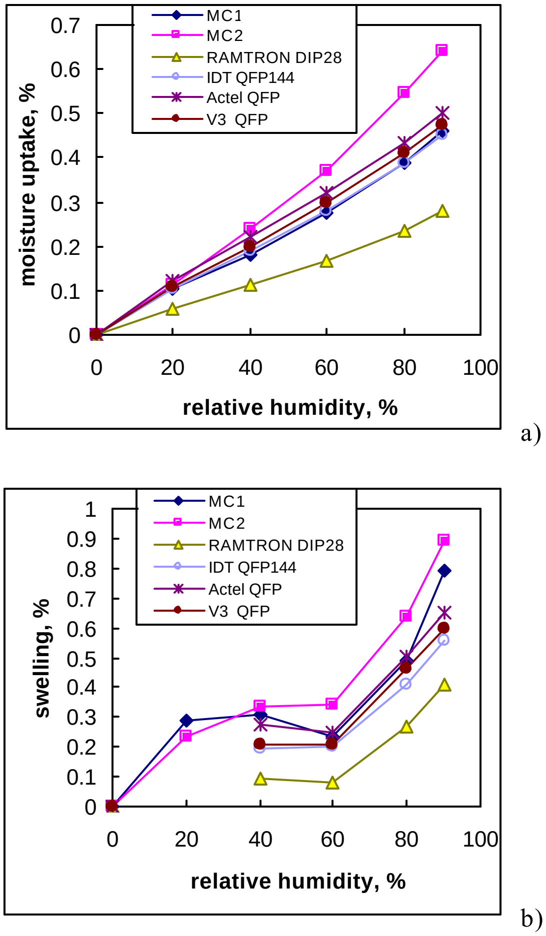

Figure 1. Isotherms of the equilibrium moisture uptake (a) and volume swelling (b) at 85 ^{o}C for epoxy molding compounds and plastic packages.

All plastic packages and molding compounds manifested similar moisture uptake and swelling sorption isotherms. The moisture uptake is virtually a linear function of relative humidity suggesting that the concentration of moisture in epoxy polymers follows Henry's law [10], and the moisture uptake at equilibrium conditions increases linearly with the pressure of moisture vapor (P):

$$dM_{\infty} = h \times P = h \times P_s \times f$$

where P_s is the pressure of saturated water vapor, f is the relative humidity, and η is the sorption coefficient, which exponentially decreases with temperature [11].

The moisture swelling isotherms had a sigmoidal shape; the volume did not changed significantly when moisture soaking was performed between 40% and 60% of relative humidity and then linearly increased at RH > 60%. This resulted in increase of the CME from ~ 0.3 to ~ 0.55 when RH increased from 60% to 90%. Minimal CME values for MCs and PEMs were observed at ~ 60% RH, and at lower RH the CMEs increased up to 0.67 to 0.93, suggesting higher efficiency of moisture to cause swelling at low humidity.

Additional experiments showed that the coefficient of hygrothermal expansion depends also on baking conditions, increasing at high temperature bakes (at T > 200 °C).

4. Environmental effects in voltage reference microcircuits

Sorption isotherms of output voltages in the microcircuits were obtained in experiments similar to those for molding compounds. Measurements after long-term storing at laboratory conditions (T = 22 °C, RH = 50%) were used as baseline data for calculation of the output deviations. Then the measurements were repeated after bake and storing for 1 week in a humidity chamber at 85 °C, with relative humidity varying from 20% to 90%. Results of these experiments are shown in Figure 2.

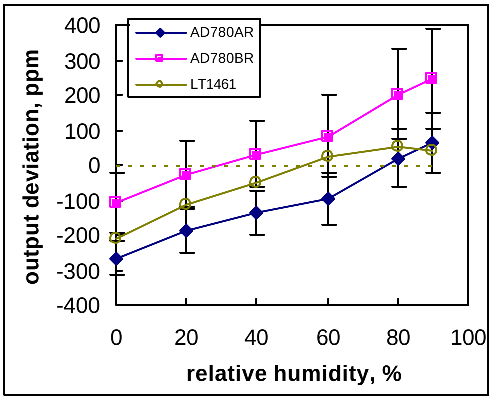

Figure 2. Effect of humidity during storing at 85 °C on deviation of the output voltage.

All parts manifested an increase in the voltage outputs with humidity. The dV_{out}-RH curves for AD780 AR and AD780BR parts were similar and had a slight sigmoidal shape. A different position of these curves along the ordinate axes is probably due to a different initial level of mechanical stresses in the parts. Saturation of the output deviation at high humidity for LT1461 parts is probably due to the plasticizing effect of moisture. This effect enhances stress relaxation in molding compounds and is probably more effective for LT1461 devices, which have MC with a lower glass transition temperature.

Moisturizing of the parts above the humidity level of laboratory conditions caused a positive shift in the output, which varied from approximately 50 to 350 ppm. Storing at low humidity conditions, below 40% to 60%, resulted in a negative shift of approximately the same value. This, in particular, indicates that due to moisture outdiffusion, a negative drift of the output of approximately 100 to 300 ppm might be expected with time in devices used in space instruments after launch, when the system starts operating in vacuum. Additional experiments have shown that an increase of temperature during testing in a humidity chamber at 85% RH from 85 °C to 150 °C (HAST conditions) increases the output deviation from ~250 ppm to approximately 400 ppm. This is a relatively small increase, considering the increase of more than 20 times of the absolute humidity in the chamber in this range of temperatures. This result can be explained considering that the moisture uptake does not vary significantly with temperature due to close values of the heat of moisture sorption and the heat of water vaporization [11].

To evaluate kinetics of the output variations during moisture desorption, characteristics of the microcircuits were measured at room temperature with time of storing at 85 °C and RH ~3%. Results of these tests are shown in Figure 3.

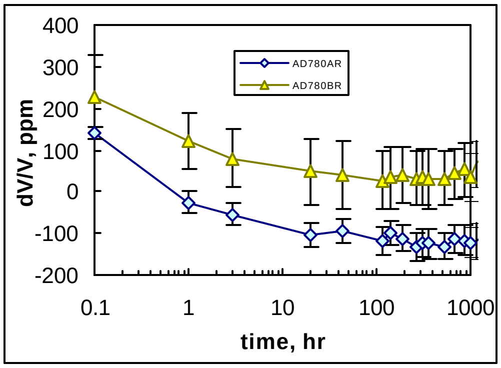

Figure 3. Output voltage deviation during moisture outdiffusion at 85 °C.

The initial positive shift of Vout was approximately 150 to 250 ppm and was caused by moisture-induced swelling. Relaxation of the output voltage was due to moisture release and occurred mostly during the first 40 to 60 hours of baking.

5. Discussion

The experiments have shown that the environmental hysteresis in voltage reference microcircuits due to swelling and shrinkage of MC can reach ± 300 to ± 400 ppm and cause failures in signal digitizing systems with resolution of 12 bits and higher. CME measurements allow for estimations of the strain in packages caused by changes in relative humidity. Assuming a linear moisture uptake and swelling isotherms, a decrease of moisture content due to baking for a part, which has been stored for a long time at laboratory conditions (22 °C, 50% RH), is ~ 0.17 % for

AD780 and ~ 0.12 % for LT1461. An increase of moisture content on approximately 0.13 % and 0.1 % is expected when these parts are exposed to 85% RH. At CME of 0.22 for AD780 and 0.27 for LT1461, the strain due to baking and due to moisture saturation at high humidity conditions would be approximately -0.037% and +0.029% for AD780 and –0.032 and +0.027 for LT1461.

To estimate the sensitivity of the output voltage to package deformations, measurements were performed on devices subjected to external mechanical stresses. The parts were measured in the range from –40 °C to +85 °C first in a free state and then after attachment to a thick (~ 4 mm) epoxy substrate. The substrate was made of room temperature curing epoxy and had an embedded resistive strain gage, which allowed monitoring of the substrate deformation during temperature measurements. Variation of the output with the package deformation was calculated at each temperature as the difference between V_{out} measured on the parts before and after attachment to the substrate. This technique allowed for obtaining V_{out} versus deformation calibration curves shown in Figure 4.

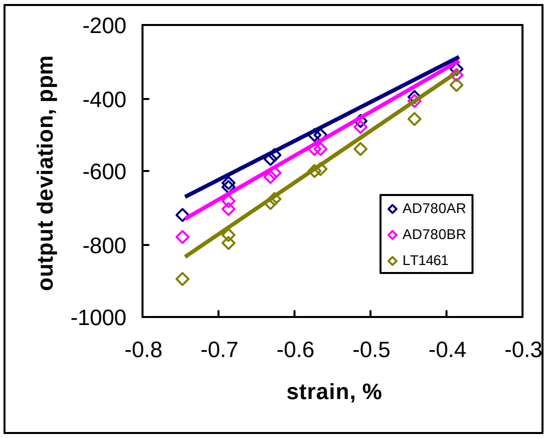

Figure 4. Variation of the output voltage for three voltage reference microcircuits caused by external compressive stresses.

The results show that under compressive stresses (negative strain), the output deviation varies linearly with strain. This allows defining a gage factor for the voltage reference microcircuit in a similar way as for the resistive strain gage measurements. The gage factor for microcircuits can be defined as a ratio of the fractional change in voltage output to the fractional change in the dimension of a part (strain), $GF = (dV/V)/(dL/L)$. The results of calculations of the gage factors and the expected output deviations due to moisture-induced strain in MC are shown in Table 3.

Table 3. Gage factors and calculated rated output deviations caused by shrinkage of molding compounds in voltage reference microcircuits.

Part	GF	Strain, %	dV/V_{calc},ppm
AD780AR	1.06	0.037	392
AD780BR	1.21	0.037	448
LT1461	1.42	0.032	454

Considering simplifications of the model and possible errors in the measurements, the calculated output variations are in reasonable agreement with the experimental data shown in Figure 2.

The kinetics of the output deviation during baking of pre-moisturized samples (Figure 3) showed that the output voltage stabilized after approximately 40 to 60 hours at 85 °C. Typical diffusion coefficient of molding compounds at this temperature is $D_{85} = 4\times10^{-8}$ cm^2/s [12]. This allows for calculation of the characteristic time of moisture outdiffusion $t_{85} = h^2/D_{85}$, where 2h is the thickness of the package. This time corresponds to the moment when approximately 90% of moisture is released from the package. At h=0.75 mm, the calculations yield t_{85} = 39 hrs, which is close to the experimental value, thus indicating that a simple diffusion model can be used to predict kinetics of the output variations in voltage reference microcircuits after environmental changes.

6. Conclusions

1. A simple, hygrostatic weighting technique has been used to assess deviations in volume of plastic packages caused by environmentally induced swelling and shrinkage of molding compounds in PEMs. The coefficient of moisture expansion of molding compounds varied from 0.1 to 0.49 when the samples were moisturized at 85 °C/85% RH conditions.
2. All tested molding compounds manifested virtually linear sorption isotherms at 85 °C. However, the swelling isotherms had a sigmoidal shape, indicating higher swelling efficiency of water molecules absorbed at low (<40 %) and high (>60%) relative humidity.
3. Environmental hysteresis due to moisture sorption/desorption processes in precision voltage reference microcircuits is large enough (up to ±300 ppm) to cause instability and failures in signal digitizing systems with resolution of more than 12 bits. Kinetics of the output variations in humid/dry conditions can be calculated based on moisture diffusion characteristics of MCs.

4. External compressive stresses resulted in negative shift of the output voltage. The estimated gage factor for the precision bandgap voltage reference microcircuits is in the range from 1 to 1.4. Estimations of the environmental hysteresis in the microcircuits based on the gage factors and moisture induced swelling and shrinkage of molding compounds are in reasonable agreement with the experimental data.

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