Effect of Temperature Gradient on Moisture Diffusion in High Power Devices and the Applications in LED Packages

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Abstract

High power electronic devices create hot spots, which give rise to the junction temperature significantly higher than the ambient temperature. This induces a situation that the moisture diffusion from environment to device is in the direction against temperature gradient direction. In addition, far field relative humidity is different from the environment surrounding the packaged devices. In this paper, two mechanisms of moisture transport are studied. First, the localized relative humidity related to the far field ambient environment is investigated. Second, moisture diffusion in the presence of temperature gradient inside package is studied. Several scenarios are investigated with the use of an LED package as example.

Introduction

Driven by the demand in compact and lightweight products, there has been a trend for ongoing miniaturization of packages. Similar trends can be observed in the development of LED packages [1,2]. One of the critical concerns is the reliability of such packages under humidity condition [3].

High power electronic devices create hot spots, which give rise to the junction temperature significantly higher than the ambient temperature. This creates the temperature gradient, not only inside electronic packages, but also the air environment that surrounds the packaged devices. According to the reliability method developed by Intel [4], it has been conceived that the hot spots in high power electronic devices, such as in CPU devices, will have localized "drying" or a reduction in relative humidity (RH) in a micro-environment. Consequently, it is predicted that the devices at on condition will have longer life than that at off condition under the same environmental humidity conditions.

In this paper, we divide the problem into two parts: moisture transport in air and solids, respectively. In air, assuming that the partial moisture pressure is in equilibrium, the relationship between the local relative humidity and the far field relative humidity can be derived. The local relative humidity and temperature can then be used as boundary conditions for solving moisture diffusion in solids. Next, the moisture diffusion in the presence of temperature gradient is investigated in package. Since thermal diffusion in solids is much greater than the moisture diffusivity, the temperature field can be solved with a steady state solution, while the moisture diffusion is treated as a subsequent transient stage analysis. As an example, the above methodology is applied to a mid-high power LED package.

Relative Humidity and Saturated Moisture Concentration in Materials

In operating conditions, heat is generated from semiconductor chips, and dissipated through package, printed circuit board, and heat sink (if any). There exists a significant temperature gradient, not only inside package, but also in air environment that surrounds the packaged device. The temperature in chassis or LEDs in a luminaire will be significantly higher than the far field ambient temperature. As a result, relative humidity near powered devices is different from the ambient relative humidity. Figure 1 and Figure 2 illustrate the local environments compared to the far field environment.

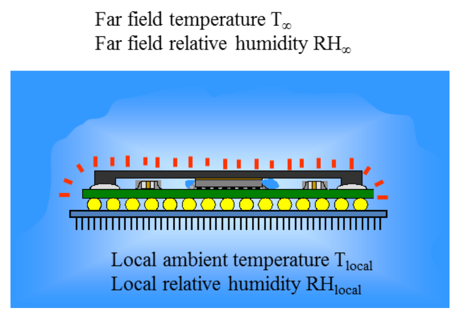

Figure 1 Far field and local field environments in an electronic package

Figure 2 Far field and local field environments in an LED lamp

The relative humidity (RH) is the percent of saturation humidity, generally defined and calculated in relation to saturated vapor density at the given temperature as follows

$$\mathrm{RH} = \frac{\text{actual vapor density}}{\text{saturated vapor density}} \times 100\% \qquad (1)$$

Or, the RH can also be approximately defined as the percent of saturated partial vapor pressure, as follows

$$\mathrm{RH} = \frac{\text{partial vapor pressure}}{\text{saturated partial vapor pressure}} \times 100\% \qquad (2)$$

This is because that vapor density can be approximated from the vapor pressure by the ideal gas law [3, 5-17]. The saturated vapor density and vapor pressure of water are given in the Appendix for convenience. Absolute humidity denotes the mass of water vapor contained in a given volume of moist air. The saturation of air limits the evaporation and thereby the release of water vapor. But this saturation level increases with the rise of temperature, as warm air can hold more moisture than a cold air. So, this absolute humidity follows the temperature closely, increasing with temperature and vice versa.

But RH is different from this. It has a particular value for a particular temperature. The value may be less for a higher temperature and high for a lower temperature as it denotes the ratio of the amount of water vapor actually present to the amount of water vapor required to saturate the air. In other words, the RH gives the degree of saturation. As the relative humidity depends upon the saturation, the variation of RH is reversed from that of temperature. So, if the temperature rises, the saturation level rises leading to less percentage of water vapor and hence less RH value.

Based on the analysis above, the RH in a micro-environment (e.g., in chassis) is related to the far-field RH as follows

$$RH_{\mathrm{local}} = RH_{\infty} \frac{p_{\mathrm{sat}}\,(T_{\infty})}{p_{\mathrm{sat}}\,(T_{\mathrm{local}})} \qquad (3)$$

by assuming that the partial vapor pressure in air remains same.

The relative humidity RH is closely related to the moisture content diffused into the absorbing solid material, such as in encapsulants in electronic devices. According to the Henry's law, the saturated moisture concentration in solid material is related to the partial vapor pressure as follows [3]

$$C_{\mathrm{sat}}(T) = \mathrm{RH}(T) \times p_{\mathrm{sat}}(T) \times S(T) \qquad (4)$$

or,

$$C_{\mathrm{sat}}(T_{\mathrm{local}}) = \mathrm{RH}_{\mathrm{local}} \times C_0(T_{\mathrm{local}}) \qquad (5)$$

where $C_0(T) = p_{\mathrm{sat}}(T) \times S(T)$. $p_{\mathrm{sat}}(T)$ is the saturated vapor pressure as function of temperature (see the Appendix), and S is the solubility, a material property, which is governed by the Arrhenius's equation

$$S = S_0 \exp\left(\frac{Q_S}{RT}\right) \qquad (6)$$

In general, $C_0(T)$ is a function of temperature T. However, for most of polymeric materials used in electronic packaging, $C_0(T)$ tends to be independent of temperature in a wide temperature range as along as it is far from glass transition temperature [7,8,10,17,15]. In this case

$$C_{\mathrm{sat}}(T_{\mathrm{local}}) = C_0 \times \mathrm{RH}_{\mathrm{local}} \qquad (7)$$

which means that the saturated concentration is linearly proportional to the relative humidity, but independent of temperature.

Consider an example where the far field environment is at 30°C with 60%RH. Assuming that the chassis temperature is as high as 60°C, equation (3) gives

$$RH_{\mathrm{local}} = \frac{31.7}{149} \times 60\% = 12.8\% \qquad (8)$$

The local RH is significantly reduced due to the rise of temperature.

It is noted that from equation (3), the saturated moisture concentration can also be written as

$$C_{\mathrm{sat}}(T_{\mathrm{local}}) = \mathrm{RH}_{\infty} \times p_{\mathrm{sat}}(T_{\infty}) \times S(T_{\mathrm{local}}) \qquad (9)$$

Moisture Diffusion in Solids

Real temperature field condition is never isothermal condition due to packages' joule heating at operation. LED packages/high power electronic devices create hot spots, which give rise to the junction temperature significantly higher than the ambient temperature. This creates the temperature gradient inside these packages. To solve the moisture diffusion, it is necessary to obtain the temperature distributions first. Since the rate of thermal diffusion is much faster than the rate of moisture diffusion [3,13], it can be assumed that thermal equilibrium is reached rapidly compared to the moisture diffusion process. Hence, only steady state temperature condition is considered. Steady state heat conduction can be solved by

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + q_0 = 0 \qquad (10)$$

with boundary conditions

$$-k\frac{\partial T}{\partial n} = h(T - T_{\mathrm{local}}) \qquad (11)$$

where k is the thermal conductivity, and h is convective heat transfer coefficient and T_{local} is the temperature in chassis, which can be approximated based on the experiments.

For moisture diffusion, for simplification purpose, one-dimensional transient equation is used

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x}\left[D(T)\frac{\partial C}{\partial x}\right] \qquad (12)$$

where C represents the moisture concentration, D refers to the diffusivity, t is the time, and x is the location. It is noted that since it is not isothermal condition, the D is function of temperature and is governed by Arrhenius's equation

$$D = D_0 \exp(\frac{-Q_d}{kT}) \tag{13}$$

where D_0 is the diffusivity constant and Q_d is the activation energy for diffusivity. The initial and boundary conditions associated with moisture diffusion are

$$C(x,0) = 0 \tag{14}$$

and

$$C|_{\text{boundary}} = C_{\text{sat}} = C_0 \times \text{RH}_{\text{local}} \tag{15}$$

When temperature gradient appears inside solids and in environments, there are three major distinctions for the above formulation from the traditional moisture diffusion analysis,

1. Since the local relative RH is applied on the component boundary, the level of relative humidity may be significantly different (lower) from the far field RH. The saturated moisture concentration of material depends RH linearly, thus, moisture concentration in component may be dropped significantly compared to the case if the far field RH is applied.
2. Since the diffusivity is the function of temperature, and increases exponentially with temperature, the moisture diffusion will be faster than the isothermal condition of the same temperature to the ambient. This implies that even though the temperature gradient is against moisture flux direction, the moisture absorption will be accelerated due to the high temperature inside (hence higher diffusivity), and it takes less time to reach to the steady state moisture diffusion state.
3. For most electronic packaging materials, the saturated moisture concentration is independent of temperature in a wide range if the temperature is away from glass transition temperature. However, in a general case, when the saturated moisture concentration is function of temperature, and increases with temperature, higher saturation level will be reached in the region of higher temperature. Even though local relative humidity at boundary gives less saturated moisture concentration of material as boundary condition, the material close to semiconductor chip has higher temperature and results in higher moisture concentration.

Case Study - LED Package

A mid-high power white color LED package is selected as a case study. Figure 3 shows the structure of the package. It is a rectangular shape LED packaging of 3mmx5.3mmx0.9mm, and is comprised of LED die, leadframe, silicone encapsulants mixed with phosphor, and PPA injection molding. The LED operates at 150mA forward current, with the correlated color temperature of 2725K. Reliability test has shown that the LED is very sensitive to humidity condition. Therefore, it is necessary to understand moisture diffusion in operating conditions. This package has a junction to lead thermal resistance of 35°C/W. To simplify the problem, the bottom surface can be considered as heat sink temperature of 80°C/W, and the local convective coefficient is 10W/m^{2}K.

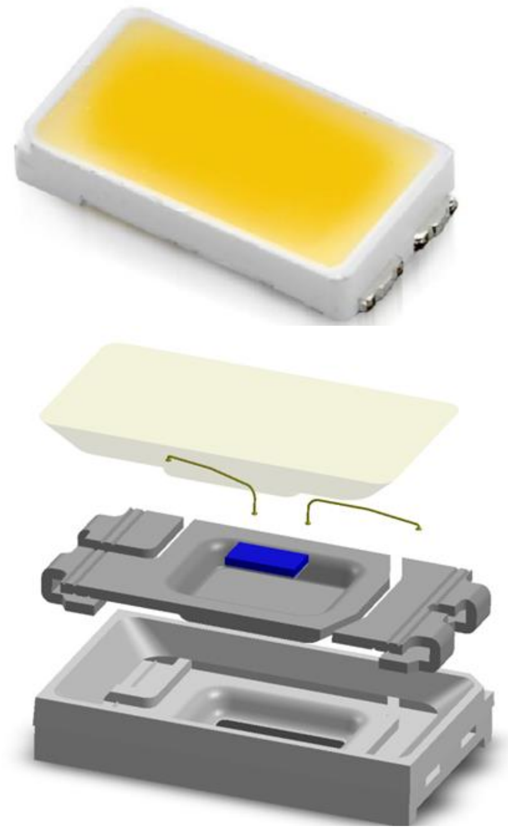

Figure 3 an LED package

Results

First, let us consider two scenarios. Scenario 1 refers to the isothermal condition with far field ambient temperature of 30°C and a relative humidity of 60%RH. Scenario 2 refers to the package that is subjected to a local ambient temperature of 60°C and 12.8%RH (as calculated in previous section in equation (8)). The objective is to find out the time to reach saturation inside package in these two scenarios. From the results in Table 1 it clearly shows that with considering the temperature gradient and local environment temperature, it takes much less time to reach saturation.

Table 1 Time to reach the saturation inside package (Scenario 1: isothermal condition with far field ambient temperature of 30□C and a relative humidity of 60%RH; Scenario 2 with a local ambient temperature and RH with temperature gradient inside package)

Scenario 1	348 hours
Scenario 2	82 hours

Next, let us investigate the local moisture concentration at the steady state for these two scenarios. Since the saturated moisture concentration is independent of temperature, the saturated moisture concentration is a linear function of RH. Therefore, from Table 2, it is obvious to note that with the consideration of local heating, regardless of temperature distribution in package, the package will absorb much less in operating condition than without considering local heating.

Further, if the saturated moisture concentration increases with temperature, there is a possibility that package will absorb more moisture even the local ambient RH is relatively low. The detailed finite element analysis on this case will be reported separately.

Table 2 Maximum moisture concentration inside package (Scenario 1: isothermal condition with far field ambient temperature of 30□C and a relative humidity of 60%RH; Scenario 2 with a local ambient temperature and RH with temperature gradient inside package)

Scenario 1	1.0 (normalized)
Scenario 2	21.3%

Concluding Remarks

1. Heat generated inside powered electronic devices in an electronic system will create a local ambient environment, such as in chassis or in a LED luminaire, where the ambient temperature is higher than the far field temperature. This will reduce the local relative humidity surrounding the package. As a result, saturated moisture concentration will decrease. This means that device at ON condition operates at less humid ambient condition than at OFF condition.
2. Heat spot in electronic devices will generate temperature gradient, and as a result, the package will be hotter than the ambient temperature. Since moisture diffusivity increases exponentially with temperature, the hotter package will accelerate the moisture diffusion. In other words, at ON condition it will take much less time to reach to the steady state moisture absorption state than at OFF condition.
3. If saturated moisture concentration increases with temperature for the materials used in electronic packages, the maximum moisture concentration inside package may be greater for a device at ON condition even though the local environment is in less humid. Because at the region close to the semiconductor chip, temperature is higher and hence, material has capacity to suck more moisture.

References

1. Zhang GQ, van Driel WD, Fan XJ. Mechanics of Microelectronics. Springer, 2006.
2. van Driel WD, Fan XJ (Eds.). Solid State Lighting Reliability: Components to System. Springer, New York. 2012.
3. Fan XJ, Suhir, E. (Eds.). Moisture Sensitivity of Plastic Packages of IC Devices. Springer, New York, 2010.
4. Sahasrabudhe S, Sane S. Fundamental concepts of reliability and mechanics in electronic packaging, ECTC PDC course notes, 2012
5. Placette MD, Fan XJ, Zhao JH, Edwards D. Dual stage modeling of moisture absorption and desorption in epoxy mold compounds. Microelectronics Reliability 52, 1401–1408. 2012.
6. Fan XJ, Zhao JH. Moisture diffusion and integrated stress analysis in encapsulated microelectronics devices. Proc. 12th. Int. Conf. on Thermal, Mechanical and Multiphysics Simulation and Experiments in Micro-Electronics and Micro-Systems (EuroSimE 2011). pp8. Linz, Austria. April 18-20, 2011.
7. Fan XJ, Lee SWR. Fundamental characteristics of moisture transport, diffusion, and the moisture-induced damages in polymeric materials in electronic packaging. in Moisture Sensitivity of Plastic Packages of IC Devices, Fan XJ and Suhir E (eds), Chapter 1, 1-28, Springer, New York, 2010.
8. He Y, Fan XJ. Real-time characterization of moisture absorption and desorption. in Moisture Sensitivity of Plastic Packages of IC Devices, Fan XJ, Suhir E (eds), Chapter 3, 71-89, Springer, New York, 2010.
9. Fan XJ. Moisture related reliability in electronic packaging. Professional Development Course (PDC) Handouts, 60th Electronic Components and Technology Conference (60th ECTC), Las Vegas, NV, USA, 2010.
10. Fan XJ, Lee SWR, Han Q. Experimental investigations and model study of moisture behaviors in polymeric materials. Microelectronics Reliability 49, 861–871. 2009.
11. Xie B, Fan XJ, Shi XQ, Ding H. Direct concentration approach of moisture diffusion and whole field vapor pressure modeling for reflow process: part I – theory and numerical implementation. ASME Journal of Electronic Packaging 131(3), 031010. 2009.
12. Xie B, Fan XJ, Shi XQ, Ding H. Direct concentration approach of moisture diffusion and whole field vapor pressure modeling for reflow process: part II – application to 3-D ultra-thin stacked-die chip scale packages. ASME Journal of Electronic Packaging 131(3), 031011. 2009.
13. Fan XJ, Zhang GQ, van Driel WD, Ernst LJ. Interfacial delamination mechanisms during soldering reflow with moisture preconditioning, IEEE Transactions on Components and Packaging Technologies 31(2), 252-259, 2008.
14. Shirangi MH, Fan XJ, Michel B. Mechanism of moisture diffusion, hygroscopic swelling and adhesion degradation in epoxy molding compounds. Proc. 41st International Symposium on Microelectronics (IMAPS), Providence, RI, USA, pp.917-923, 2008.
15. He Y, Fan XJ. In-situ characterization of moisture absorption and desorption in a thin BT core substrate. Proc. of Electronic Components and Technology Conference (ECTC), 1375-1383. 2007.
16. Fan XJ, Zhou J, Zhang GQ, Ernst LJ. A micromechanics based vapor pressure model in electronic packages. ASME Journal of Electronic Packaging 127 (3), 262-267. 2005.
17. Wong EH, Koh S, Lee KH, Rajoo R. Comprehensive treatment of moisture induced failure-recent advances.

Electronics Packaging Manufacturing, IEEE Transactions on, 25(3), 223-230. 2002.

Appendix

Table A1 Saturated vapor density and pressure of water

Temperature		Saturation Pressure				Density	
(°C)	(°F)	(Pa)	(mmHg)	(psia)	(inHg)	(kg/m^3)	10^{-3} (lb/ft^3)
0	32	603	4.6	0.09	0.18	0.005	0.30
10	50	1212	9.2	0.18	0.36	0.009	0.59
20	68	2310	17.4	0.33	0.68	0.017	1.08
30	86	4195	31.7	0.61	1.24	0.030	1.90
40	104	7297	55.1	1.06	2.15	0.051	3.20
50	122	12210	92.2	1.8	3.60	0.083	5.19
60	140	19724	149	2.9	5.82	0.13	8.13
70	158	30866	233	4.5	9.11	0.20	12.3
80	176	46925	354	6.8	13.8	0.29	18.2
90	194	69485	525	10.1	20.5	0.42	26.3
100	212	100446	758	14.6	29.6	0.59	36.9
120	248	196849	1486	28.6	58.1	1.10	68.7
140	284	358137	2704	51.9	105.7	1.91	119
160	320	611728	4619	88.7	180.5	3.11	194
180	356	990022	7475	144	292.1	4.80	300
200	392	1529627	11549	222	451.2	7.11	444