Simulation of Moisture Ingression in Microelectronics Package to Correlate Accelerated Tests and Field Conditions Reliability

[1]*Simone Antonio Sala,* [1]*Lucia Zullino,* [2]*Roberta Cattaneo,* [2]*Sonia Morin,* [1]*Luca Cecchetto,* [1]*Antonio Andreini,* [1]*Marco Rovitto,* [1]*Alberto Mancaleoni*

[1]STMicroelectronics srl, via C. Olivetti n. 2 Agrate Brianza (MB), Italy; Phone: +39 039 603.1

[2]STMicroelectronics srl, via Tolomeo n. 1 Cornaredo (MI), Italy; Phone: +39 02 93519.1

Email: simone.sala@st.com

Introduction

Plastic packages, coated with Epoxy Molding Compound (EMC) can provide an economic and versatile protection to the integrated circuits (IC) from mechanical damage. A major drawback of molded packages is that they are not hermetic and are prone to absorb moisture from external environment. Moisture is one of the principal causes of several package failure mechanisms: degradation of adhesion strength, popcorn effect during soldering and electrochemical corrosion are well-known examples [1]. Moisture migrates through molding from external environment to silicon die, where it leads to corrosive reactions on metal layers of interconnections levels.

Many works [2, 3] use a physical model based on the phenomenon of diffusion of moisture in solid materials, which depends on the environmental conditions as well as on some material properties. Relevant diffusion properties are diffusivity and moisture saturation concentration, and they can be determined performing dedicated experiments on test samples under reference environmental conditions.

Purpose of this paper is to describe a series of simulations of moisture absorption in EMC under different test and field conditions. As described in many works [4, 5], moisture moving inside package can be approximated using a model based on Fick's laws of diffusion. The model is then developed into multi-material simulations, adding an air gap between EMC and silicon die, to reproduce the effect of EMC-Die delamination. The presence of the air gap also allows to make local evaluations of Relative Humidity (RH) inside the package and to estimate the possibility of dew formation over die surface. An acceleration factor based on total moisture absorption is also proposed to correlate accelerated tests with field life conditions.

Physical background and material properties

Fick's laws are a good approximation to describe moisture diffusion phenomenon inside polymers [6].

The first law describes diffusion phenomena under the assumption of steady state:

$$\vec{\boldsymbol{J}} = -\boldsymbol{D}\boldsymbol{\nabla}\mathbf{c} \qquad (1)$$

J is the flux of the diffused species, **D** is the diffusion coefficient or diffusivity of material and **c** is the water concentration. The second law predicts how diffusion causes the concentration to change with time:

$$\frac{\partial c}{\partial t} = \boldsymbol{D}\boldsymbol{\nabla}^2\mathbf{c} \qquad (2)$$

Diffusivity is a temperature-dependent material property, and can be described by the Arrhenius equation, since it is an activated process:

$$\boldsymbol{D} = \boldsymbol{D_0}\boldsymbol{e}^{-\frac{E_a}{kT}} \qquad (3)$$

$\mathbf{D_0}$ is a reference diffusivity, $\mathbf{E_a}$ is diffusivity activation energy, **k** is Boltzmann constant and **T** temperature. Another relevant material property is the saturation concentration ($\mathbf{c_{sat}}$), which is the maximum possible water gain of a material at a given environmental conditions; c_{sat} can be described using Henry's law [7]:

$$\boldsymbol{c_{sat}} = \boldsymbol{S} \cdot \boldsymbol{p_{ext}} \qquad (4)$$

S is the solubility and $\mathbf{p_{ext}}$ is the ambient vapor pressure, which depends on saturated vapor pressure ($\mathbf{p_{sat}}$) and RH as follows:

$$\boldsymbol{p_{ext}} = \boldsymbol{RH} \cdot \boldsymbol{p_{sat}} \qquad (5)$$

Solubility and saturated vapor pressure are both temperature dependent and follow the Arrhenius equation. Anyway, in many polymer-based packaging materials, temperature dependence is a minor contribution or can even be neglected, and so c_{sat} depends mostly on RH [8].

Absorption curves can be used to determine experimentally materials properties. Reference procedure for EMC is described in JEDEC Standard JESD22-A120A [9]; a specimen is put inside an environmental chamber and moisture absorption as weight gain is measured until saturation (at least 360 hours). The EMC under study for this work will be referred as EMC A. Diffusion coefficient and saturation concentration are calculated from absorption curves provided by the supplier. See Figure 1 for details.

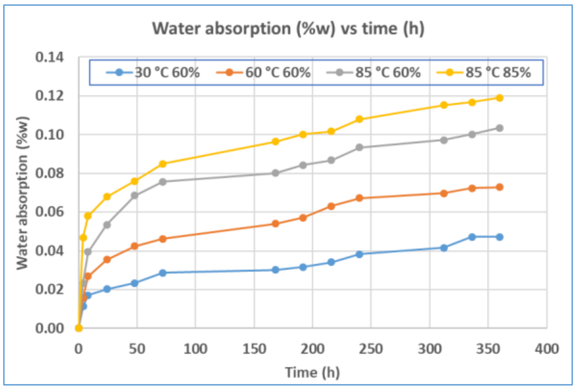

Figure 1: absorption curves of EMC A

The activation energy for water diffusion (E_a) can be extrapolated from this curves and it is 0.19 eV; this value is comparable with those of other materials reported in literature works [1].

Simulation set-up and COMSOL implementation

The package studied in the simulation is TQFP64 (Figure 2). All simulations use a 3D model; thanks to geometrical symmetry, only a quarter of device can be considered.

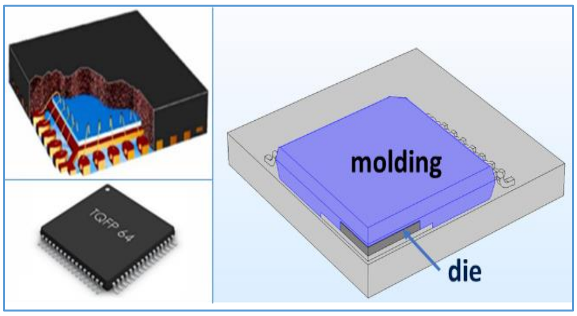

Figure 2: picture and model of TQF64

Water diffusion is evaluated only inside EMC; water is absorbed from the environment only through molding external surfaces (see Figure 3). Surface and interface phenomena (such as adsorption) are not taken into consideration.

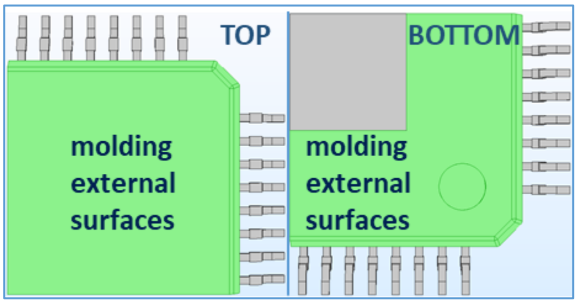

Figure 2: geometry of simulated device

The main module used is *Transport of Diluted Species* and it is applied to the molding domain. Diffusion coefficient is the only property that defines water diffusion behavior and is required in the *Transport Properties* module, while saturation concentration is used as boundary condition (*Surface Concentration* module) and defines absorption at external surfaces, which are supposed to be in equilibrium with the environment.

Moreover, to simulate the case of possible delamination between molding and die, a thin layer (20 µm) of dry air is interposed between molding and die in other simulations (see Figure 4). Delamination at the EMC-Die interface is not allowed by quality criteria, but current detection techniques are not able to detect the smallest voids and so it is important to understand the impact of this worst case condition in particular from a reliability point of view.

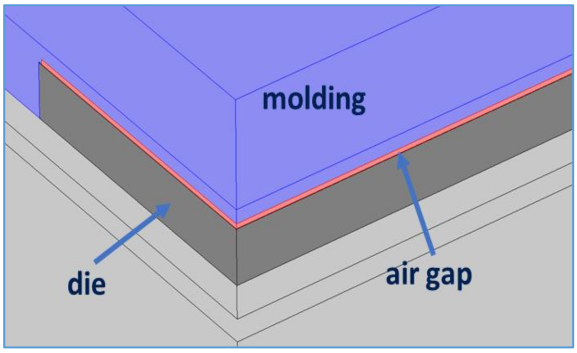

Figure 4: air gap between molding and die

Air properties are taken from literature [10-11], with dependency from RH and T in the range 0 – 100 °C.

The dependent variable of this physics is (water) concentration **c**; it is calculated in the entire volume of molding and in particular it is evaluated as *derived value* at molding-die interface (see Figure 5), where corrosion issues can occur.

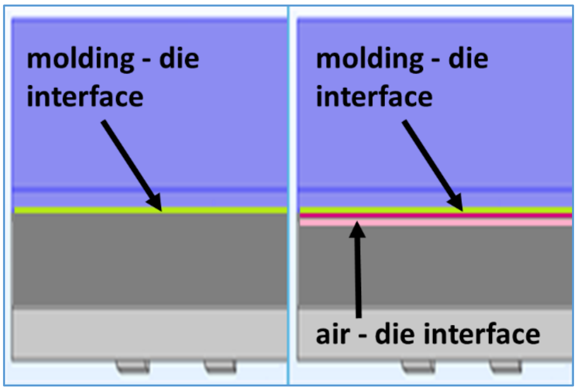

Figure 5: detail of interfaces under study

In presence of the air gap, there is also the molding-air interface to be taken into consideration. This interface can represent a problem in a finite element simulation since the two adjacent materials have different absorption capacities: so water concentration is discontinuous. To overcome this issue, the so-called "normalization approach" is used and a "normalized" variable, continuous at the interface, is defined. It is called fractional saturation (**c***) [1, 12]:

$$c^* = c/c_{sat} \tag{6}$$

The normalization factor used is the saturation concentration of each material (according to where it is calculated) and it substitutes c as in-simulation variable. "Real" concentration c is re-calculated during data processing by removing the normalization. The module *Heat Transfer in Solids* is also used, in particular the ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) database for real world environmental data, to study RH inside the air gap (module *Fluid*). All studies of simulations are time-dependent.

Simulation case studies and results

Temperature Humidity Bias conditions – molding only (no air gap)

Temperature Humidity Bias (THB) testing is a reliability test designed to accelerate metal corrosion, with particular focus on thin metallization at the die surface. THB testing employs the following stress conditions inside an environmental chamber: 2000 hours at 85 °C, 85% RH, with bias applied to the device, according to standard JEDEC JESD22-A101. In this-work bias is not simulated. In table 1 absorption properties for EMC are reported.

T	RH	D	C_{sat}
85 °C	**85%**	**8.4E-13 m²/s**	**162 mol/m³**

Table 1: EMC A properties in THB loading conditions

In simulation, initial value of c is 0, which means the molding is completely dry. Figure 6 reports water absorption (as weight gain) evaluated at molding-die interface during the test.

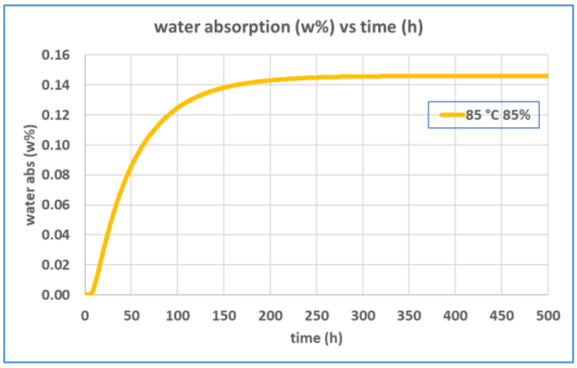

Figure 6: water absorption at molding-die interface

Saturation on the die surface is reached after about 260 hours. Figure 7 is a graphical representation of water penetration inside molding cross-section at different hours, while Figure 8 is a depth profile over time.

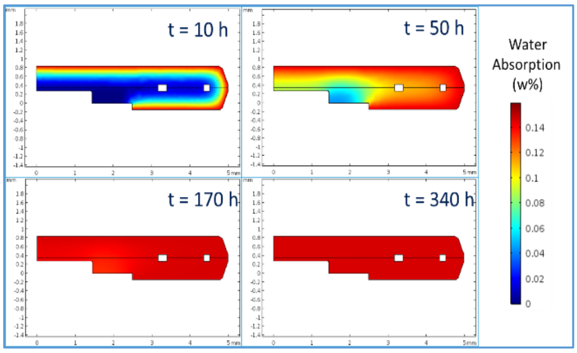

Figure 7: moisture penetration in cross section

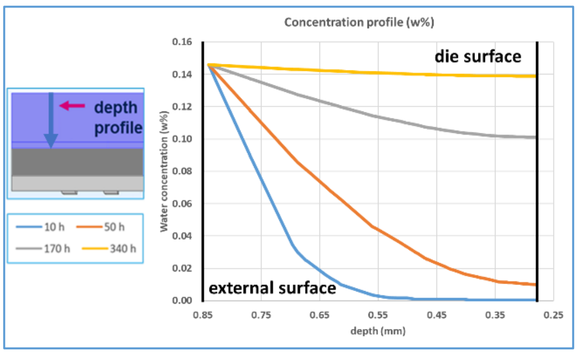

Figure 8: depth profiles

Temperature Humidity Bias conditions – molding and air gap

The presence of the air gap does not change too much water concentration at molding interface, and also absorption trend at air-die interface is comparable (see Figure 9). In Table 2 diffusion properties of air are reported. Diffusion coefficient of molding is much smaller and determines diffusion trend in both layers.

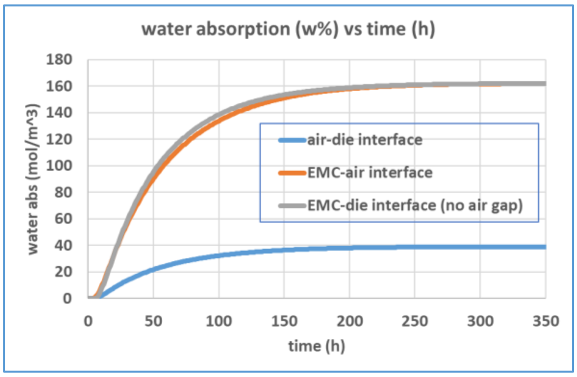

Figure 9: water absorption with air gap

T	*RH*	*D*	C_{sat}
85 °C	**85%**	**3.4E-5 m^2/s**	**39 mol/m^3**

Table 2: Air properties in THB loading conditions

Because of air high diffusion coefficient, water concentration is constant inside the air gap, as shown in depth profile in Figure 10.

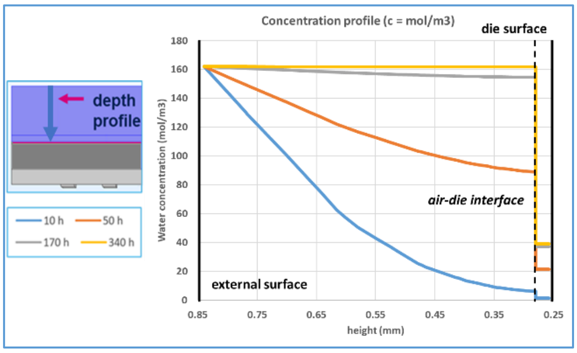

Figure 10: depth profile

Inside the air gap it is also possible to evaluate RH. As shown in Figure 11, 100% is reached in about two days, and water condensation can occur.

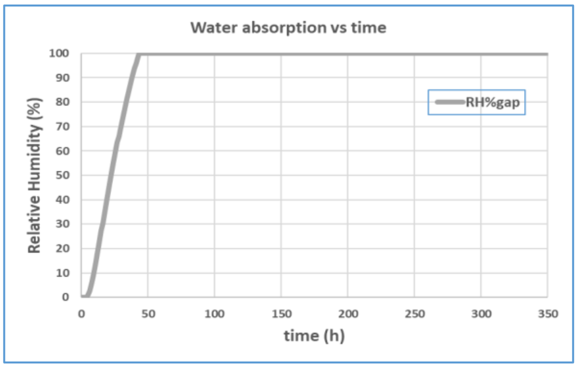

Figure 11: RH% inside air gap

Thermal Humidity Cycling – molding and air gap

Environmental tests are described in several other standards, for example IEC60068-2-30 [15] or JESD22A104E [16]. Temperature and RH can cyclically oscillate according to one of the profiles allowed by the standard. One of these is considered in the following simulation. RH is kept constant at 93% and temperature oscillates between 30 and 85 °C (see Figure 12 for details).

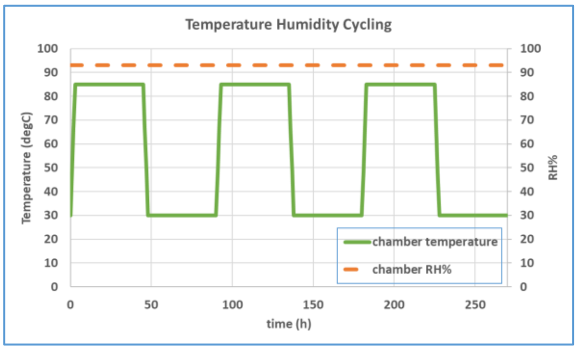

Figure 12 temperature profile during 1 cycle

This test was conceived to induce dew formation over die surface and reproduce conditions to evaluate the risk of corrosion phenomena. Each cycle lasts 96 hours; full test is 3 cycles (288 hours in total). Dew point is calculated according to equation from literature [12]

Results are reported in Figures 13 and 14. Dew formation is actually confirmed by simulations during stay at 30 °C, where dew point is equal to test chamber temperature. Dew presence is also confirmed by *Condensation Indicator* of *Heat Transfer* module, an indicator that switches from 0 to 1 when there are the conditions for water to condensate.

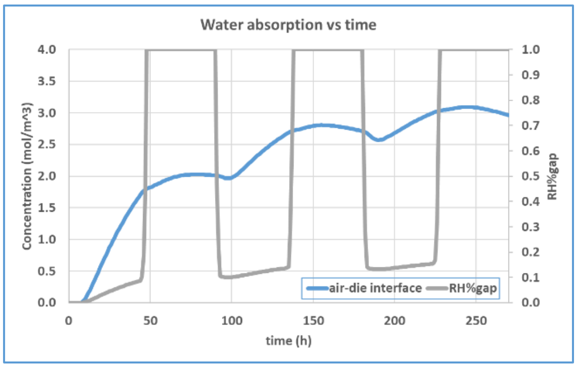

Figure 13 moisture absorption during cycling

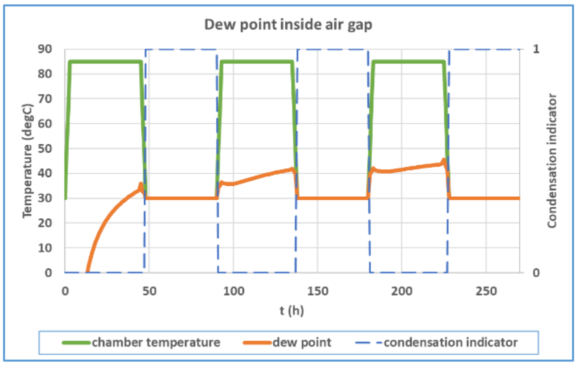

Figure 14 dew formation during cycling

Field conditions - molding and air gap

The climate of the city of Miami (Florida, USA), a typical humid subtropical climate, has been chosen to evaluate moisture absorption in field conditions.

The weather profile is set to define a worst case scenario, with temperature and RH that are the maximum values available in the ASHRAE database, without considering a specific historical year (see Figures 15 and 16). An entire year has been simulated, 24/7 (8760 hours in total).

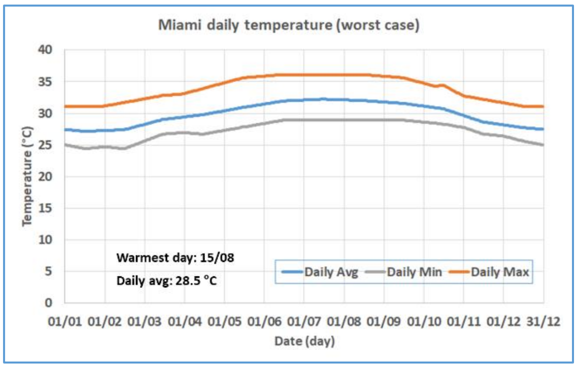

Figure 15: temperature of Miami worst case climate; daily average, minimum and maximum

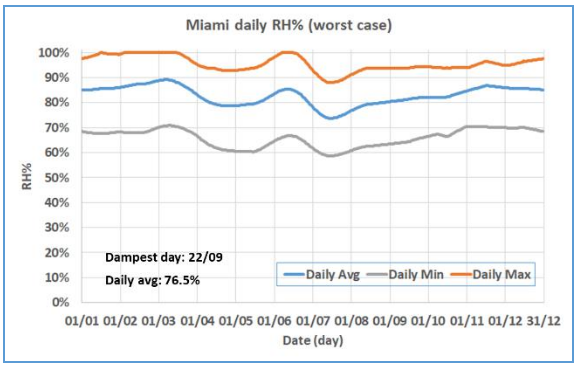

Figure 16: RH% of Miami worst case climate; daily average, minimum and maximum

Absorption and saturation have an oscillatory trend due to weather daily and seasonal variation. Figures 17 and 18 show the trends at molding-air interface and air-die interface. Maximum absorption is reached in the month of June.

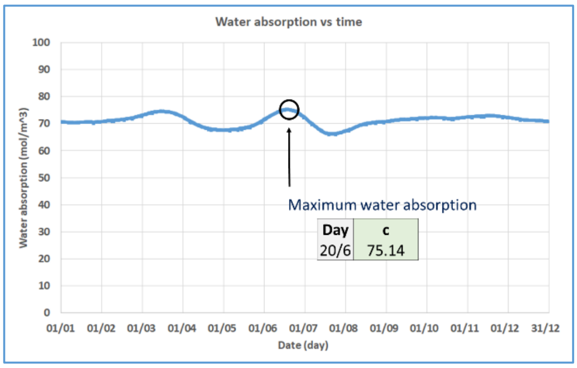

Figure 17: water absorption at molding-die interface

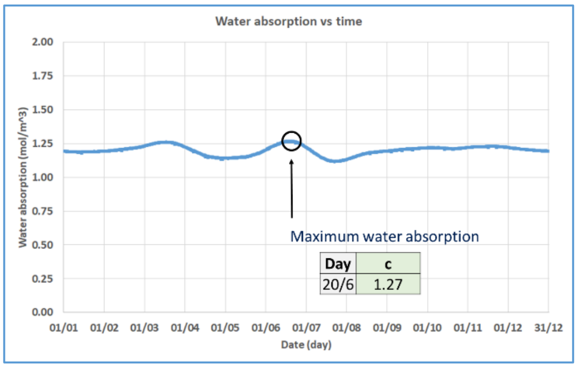

Figure 18: water absorption at air-die interface

Unlike what happens in THB, in this situation RH never reaches 100% (Figure 19). Maximum value is 98% and is reached during February.

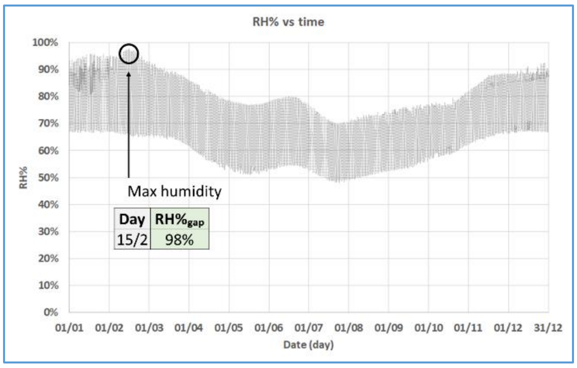

Figure 19: RH inside air gap

Comparison between results and estimation of an acceleration factor

Environmental conditions in THB seem to be more severe than the ones in the real world climate that has been simulated. Maximum temperature in Miami is 36°C, while RH can reach 100% but for only few hours. From a reliability point of view, THB has actually the effect to accelerate water diffusion phenomena that occurs on the field.

To compare different stressing conditions, it is possible to estimate an acceleration factor for water absorption in THB test and Miami climatic conditions, considering for example the time needed to reach the same cumulative amount of water absorbed at air gap-die interface. In Figure 20 there is a graphic representation of this comparison, which takes in account moisture absorption in the two case studies.

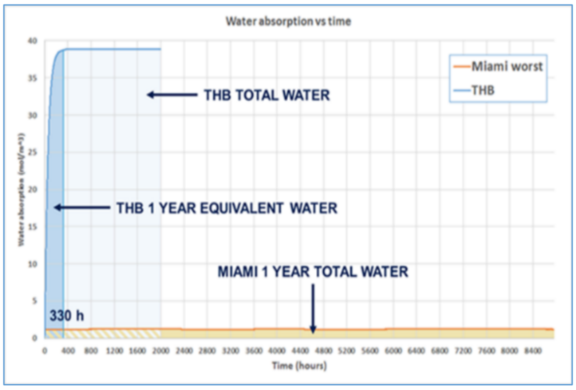

Figure 20: comparison chart between THB and Miami climate

The orange curve is the yearly trend from Miami climatic conditions and the orange area is the cumulative water absorbed in one year. The blue curve is the trend during 2000 hours THB and the two areas are the cumulative absorbed water during the entire THB test (light blue area) and the portion of the cumulative absorbed water in THB equivalent to the water absorbed in one year in Miami worst climatic conditions (heavy blue area, it has the same area of the orange area).

About 330 hours in THB conditions are enough to have the same cumulative water gain than one year (8760 hours) in Miami environment, with an acceleration factor of 27. This means that 2000 hours THB test actually simulates more than 6 years of field application.

Moreover, it is important to consider the fact that during THB RH is almost always at 100%, while this never occurs in Miami climate. This implies that the test could introduce other phenomena that are not present in field, inducing for example risks for corrosion issues that are less probable to occur in real applications.

Conclusions

Using COMSOL Multiphysics, a model to evaluate moisture diffusion inside EMC has been developed. Starting point was the physics of Fickian diffusion in solids and materials properties obtained from absorption curves. An air gap between molding and the encapsulated silicon die has been also considered to evaluate a worst case scenario and to make further evaluation due to the presence of air.

The model has been used to study different loading conditions: reliability tests in static and cyclic temperature and relative humidity conditions, and field conditions (in particular Miami climatic environment). Results have been analyzed to assess the risk of dew formation, that is one of the necessary conditions to cause corrosion phenomena and device failure during application.

A comparison between test and field conditions has been also done to understand if accelerated tests could induce different absorption conditions and so reliability issues that are not significantly activated in real applications.

References

[1] J. Wang, R. Liu, D. Liu, S. Park, Advancement in simulating moisture diffusion in electronic packages, Microelectronics Reliability 73 (2017) 42–53

[2] M. Tencer, Moisture ingress into nonhermetic enclosures and packages. A quasi-steady state model for diffusion and attenuation of ambient humidity variations, Electronic Components and Technology Conference, 1994. Proceedings, 44th Edition (1994)

[3] M.H. Shirangi, B. Michel, Mechanism of Moisture Diffusion, Hygroscopic Swelling, and Adhesion Degradation in Epoxy Molding Compounds - Moisture Sensitivity of Plastic Packages of IC Devices, Spinger (2010)

[4] D. Liu, J. Wang, R. Liu, S.B. Park, An examination on the direct concentration approach to simulating moisture diffusion in a multi-material system, Microelectronics Reliability 60 (2016) 109–115

[5] E.H.Wong, S.B. Park, Moisture diffusion modeling – A critical review, Microelectronics Reliability 65 (2016) 318–326

[6] M.H. Shirangi, X.J. Fan, B. Michel, Mechanism of Moisture Diffusion, Hygroscopic Swelling and Adhesion Degradation in Epoxy Molding Compounds

[7] A. Mavinkurve, J.L.M. Llacer Martinez, M. van Soestbergen, J.J.M. Zaal, Moisture absorption by molding compounds under extreme conditions: Impact on accelerated reliability tests, Microelectronics Reliability 64 (2016) 254–258

[8] M. Zhang, S.W.R. Lee, A novel vapor pressure transfusion model for the popcorning analysis of Quad Flat No-lead (QFN) packages, 3rd Electron. Sys. Integ. Tech. Conf 2010, pp. 1–9.

[9] JESD22-A120A, Test Method for the Measurement of Moisture Diffusivity and Water Solubility in Organic Materials Used in Integrated Circuits, JEDEC SOLID STATE TECHNOLOGY ASSOCIATION, January 2008

[10] J.L. Monteith, M.H. Unsworth (1990) Principles of environmental physics, Edward Arnold; London, etc.

[11] R.C. Weast, (Ed.) (1986) Handbook of Chemistry and Physics CRC Press Inc.; 67th edition; Boca R aton, Florida, USA.

[11] H. Walter, M. van Dijk, Moisture Phenomena in Polymers and Effects on Microelectronic Reliability, EuroSime 2018 proceedings

[13] M. G. Lawrance, The Relationship between Relative Humidity and the Dewpoint Temperature in Moist Air: A Simple Conversion and Applications, Bulletin of the American Meteorological Society, Volume 86 No. 2 February 2005

[14] JESD22-A101, Steady State Temperature Humidity. Bias Life Test, , JEDEC SOLID STATE TECHNOLOGY ASSOCIATION, March 2009

[15] IEC60068-2-30, Environmental testing, INTERNATIONAL STANDARD, August 2005

[16] JESD22-A104E, Temperature Cycling, JEDEC SOLID STATE TECHNOLOGY ASSOCIATION, October 2014