Moisture absorption and desorption in wafer level chip scale packages

K. Rongen a,⁎, A. Mavinkurve a, M. Chen b, P.J. van der Wel a, F.H.M. Swartjes a, R.T.H. Rongen a

a NXP Semiconductors Nijmegen, Netherlands
b NXP Semiconductors Kaohsiung, Taiwan

Abstract

Life tests standards for qualification like published by JEDEC have been set-up for traditional lead frame or substrate based packages. One of the standards simulates the transport and the PCB-soldering of products, JESD22-A113F. The simulation starts with a soaking step during which the products absorb moisture. The objective of this paper is to study in detail the dynamics of moisture absorption and desorption for Wafer Level Chip Scale Package (WLCSP) devices that contain moisture absorbing repassivation layers, typically of polyimide material, during preconditioning. Weighing experiments are presented, with fundamental implications. In this paper, a shortened soaking step at lower temperature (24 h/30 °C/85%RH) is proposed for WLCSP-preconditioning. And the data that are presented even show that soaking may be skipped at all.

1. Introduction

Due to its small dimensions and low costs, the Wafer Level Chip Scale Package (WLCSP) has become very attractive in recent years, especially in portable applications. Typically, such packages contain thin organic materials like polyimides, used as redistribution layers or to provide stress relief. Such materials are sensitive to moisture absorption; however limited literature is published on this subject [Ref.1,2]. Polyimides are a class of usually thermos-setting polymers that are known for their thermal stability. They can be patterned using conventional lithographic processes.

Moisture absorption is a special concern in the treatment of WLCSP devices during what is called preconditioning. Preconditioning is mandatory for Surface Mounted Devices (SMD) prior to environmental reliability tests [3], like Temperature Cycling (TC) [4] and Highly Accelerated Stress Test (HAST). It simulates the real life aspects of the devices from the moment they are manufactured at the component supplier until PCB assembly at the component user. This means it covers transport, warehouse storage and storage under shop floor environmental conditions. One important aspect simulated in preconditioning is the fact that SMD devices absorb moisture during transport and storage that will be released suddenly when they are subjected to high solder temperatures during PCB mounting. As a result, internal damage may occur from delamination until severe body cracking, better known as popcorn. If SMD devices are sensitive to absorb moisture, a soaking step is mandatory according to Ref. [5]. This is quite common for conventional moulded packages. However, for WLCSP it is unclear if and how fast or how much moisture they absorb. The objective of this paper is to study in detail the dynamics of moisture absorption and desorption for WLCSP devices that contain moisture absorbing layers, e.g. polyimide material, during preconditioning. The gained insight will be used to define how to perform preconditioning on WLCSP devices, which will be proposed to JEDEC.

2. Experimental

2.1. Preconditioning steps

A semiconductor component user expects from a component supplier that the moisture sensitivity is classified according to levels defined per Ref. [6]. During reliability qualification of the component, the devices shall be preconditioned according to the classified level following the steps as described in Ref. [5]:

1) Devices are subjected to 5 temperature cycles to simulate the shipment by air plane. The conditions are − 40 °C to 60 °C. This step is optional.
2) This is followed by a dry bake step of 24 h, at 125 °C, to reset the moisture level to zero.
3) Then, the devices are soaked according to conditions specified in Ref. [6]. The purpose of this step is to simulate the moisture absorption during transport, storage in a warehouse and subsequent floor life at the component user before PCB mounting. This step can be

⁎ Corresponding author.
E-mail address: kirsten.rongen@nxp.com (K. Rongen).
skipped if evidence is provided that parts do not absorb humidity. For components having an unlimited floor life (at 30 °C and 85%RH), this is accelerated by exposing the part for 168 h at 85 °C / 85%RH. This is called Moisture Sensitivity Level (MSL) 1.

4) The soaking is followed by the actual PCB mounting simulation, in which the devices are exposed to a temperature profile, in which the peak temperature is determined by the package body and thickness. For this step a hot convection reflow furnace for PCB assembly is used. This is performed three times to assure that the parts can withstand multiple soldering steps. It is known that the high solder temperatures of 240 to 260 °C, may create damage for conventional packages via internal delamination or even cracks that limit the reliability robustness.

5) Finally the devices are immersed in flux, to allow flux constituents to enter the package body via damage provoked by the previous step. In order not to contaminate life test equipment in the subsequent reliability tests (like TC and HAST), parts have to be rinsed and dried. This step is called flux dip.

In Fig. 1, the first steps out of JEDEC are schematically shown.

2.2. Test structures

Two schematic WLCSP-devices are shown in Fig. 2. a) shows a construction with polyimide repassivation layer, b) shows a redistribution layer (RDL) with additional repassivation layer.

For the absorption–desorption experiments, two different approaches have been used.

The first approach is to weigh actual WLCSP devices with a high accuracy balance. To that extent, two 12 in. wafers consisting of actual WLCSP devices, were cut into wafer pieces of 22.5 × 29.3 mm². Wafer pieces with two different polyimide materials (1 and 2) have been used. The thickness of the polyimide layer was about 5 μm. With the corresponding volume and densities, the expected mass ratio between dry and soaked device is determined, to estimate whether the method will be accurate enough. With a typical mass of the wafer pieces of around 10 g, a polyimide mass on that wafer piece of about 0.04 g, and a typical value of 1% for the humidity uptake during soaking, a mass increase of about 0.0004 g is expected. This turns out to be just within the accuracy of the balance that was used to run the experiments.

Fig. 1. The temperature profile for the steps described in Section 2.1 [5], up and including the first PCB mounting reflow step is shown schematically (left axis). In the same graph, the change on moisture level in the moisture absorbing material is shown schematically (right axis).

Fig. 2. a) Schematic WLCSP with polyimide repassivation and b) redistribution layer (RDL) and additional repassivation layer [5].

Please cite this article as: K. Rongen, et al., Moisture absorption and desorption in wafer level chip scale packages, Microelectronics Reliability (2015), http://dx.doi.org/10.1016/j.microrel.2015.06.129
In the second approach, the accuracy was increased, by taking polyimide foils with a thickness of about 33 μm and a total weight of 0.5 g per sample. These foils were specially prepared by the polyimide material 2 supplier. This model system allowed for significantly more moisture uptake, simply because the polyimide total volume was considerably larger than on the actually bumped wafers. In addition to this, measurements were performed on 80 μm KAPTON® foil to verify the saturation values as well as the diffusion constants. As a result, both absorption and desorption of moisture could be determined with a higher accuracy, even allowing to determine diffusion parameters for modelling.

2.3. Test conditions and evaluation

Both the pieces of wafers with bumped devices and the polyimide foils were subjected to the different steps in preconditioning. This is shown in Table 1.

The bumped wafer pieces were weighed:

- as received,
- after dry bake for 24 h at 125 °C,
- during soaking after 1, 2, 4, 7, 24, and 168 h at 2 conditions: a) 85 °C / 85%RH and b) 30 °C / 85%RH,
- after pre heat for 2 min at 150 °C,
- after solder heat at 240 °C and 260 °C.

Reference pieces were measured in parallel to eliminate other environmental influences.

The polyimide foils were weighed:

- as received,
- after dry bake for 24 h at 125 °C,
- during soaking after 0.5 1, 2 and 3.5 h at 2 conditions: a) 85 °C / 85%RH and b) 30 °C / 85%RH,
- after pre-heat for 1, 2, 3 and 5 min at 150 °C.

Materials 1 and 2 are both polyimide-based but from different suppliers.

---

**Table 1**

Overview of executed weight measurements. The numbers in brackets refer to Fig. 1, the stages during the preconditioning, relevant for this study [5].

<table>
<thead>
<tr>
<th>Test structure</th>
<th>Precondition steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bumped wafer pieces with PI material 1</td>
<td>Yes (2) Soak (3) Preheat (4a) Solder heat (4b)</td>
</tr>
<tr>
<td>Bumped wafer pieces with PI material 2</td>
<td>Yes (2) Soak (3) Preheat (4a) Solder heat (4b)</td>
</tr>
<tr>
<td>PI foil material 2</td>
<td>Yes (2) Soak (3) Preheat (4a)</td>
</tr>
</tbody>
</table>

---

### Test conditions and evaluation

Both the pieces of wafers with bumped devices and the polyimide foils were subjected to the different steps in preconditioning. This is shown in Table 1.

The bumped wafer pieces were weighed:

- as received,
- after dry bake for 24 h at 125 °C,
- during soaking after 1, 2, 4, 7, 24, and 168 h at 2 conditions: a) 85 °C / 85%RH and b) 30 °C / 85%RH,
- after pre heat for 2 min at 150 °C,
- after solder heat at 240 °C and 260 °C.

Reference pieces were measured in parallel to eliminate other environmental influences.

The polyimide foils were weighed:

- as received,
- after dry bake for 24 h at 125 °C,
- during soaking after 0.5 1, 2 and 3.5 h at 2 conditions: a) 85 °C / 85%RH and b) 30 °C / 85%RH,
- after pre-heat for 1, 2, 3 and 5 min at 150 °C.

Materials 1 and 2 are both polyimide-based but from different suppliers.

---

**Figure 3.** Weight measurements on bumped wafer pieces for two polyimide materials at different soaking conditions. Exponential lines were fitted through these with the weight after dry bake was taken as reference “zero-value”.

**Figure 4.** a (top) and b (bottom). Measurement data on foil material 2 shows that saturation is obtained well within 1 h under both conditions: 4a) 30 °C / 85%RH; 4b) 85 °C / 85%RH. The solid lines are fitted based on Eq. (1), D(30 °C): $3.6 \times 10^{-4}$ mm²/h, D(85 °C): $8 \times 10^{-4}$ mm²/h.

**Figure 5.** Weight measurements on bumped wafer pieces as received (0 h), after pre-heat and solder heat for polyimide materials 1 and 2.
3. Results

3.1. Absorption

For the bumped wafer pieces the weight increase (after dry bake) as a function of time is shown in Fig. 3 for the two conditions and the two polyimide materials (1 and 2).

Within the accuracy of measurements, the bumped wafer pieces as received had the same level of absorption as after soaking for 24 h. There is no increase observed anymore from 24 to 168 h soaking. Unlike the measurements done on KAPTON® foil, described later and in Fig. 8, the data on wafers did not enable us to draw conclusions about the temperature dependency of moisture saturation value. For polyimides it has been shown in the literature that the temperature has no influence on the moisture saturation and that the %RH is the main determining parameter [1,2].

These expectations are confirmed by the more accurate soaking experiments on the 33 μm thick polyimide foils. This is shown in Fig. 4, from which it can be concluded that saturation already occurs well within 1 h, under condition 30 °C / 85% R.H. (Fig. 4a), as well as under condition 85 °C / 85% R.H. (Fig. 4b).

The experimental data is fitted with a simple 1D Fick’s diffusion model [7] as given in Eq. (1).

\[ \frac{M_t}{M_\infty} = 1 - \frac{8}{\pi^2} \exp \left( -\frac{\pi^2 D t}{l^2} \right) \quad \text{for } M_t/M_\infty > 0.5 \]

where

- \( D \) diffusion constant,
- \( t \) time,
- \( l \) sample thickness (half in the case, diffusion takes place from both free surfaces),
- \( M_t \) moisture concentration at time \( t \),
- \( M_\infty \) moisture concentration at saturation.

Within the measurement accuracy, we can conclude that the moisture uptake at saturation is about the same, viz. ~0.8% by weight.

3.2. Desorption

After drying the bumped wafer pieces for only 2 min at 150 °C (pre-heat stage), the moisture content decreased to values very similar to the levels after the dry bake of 24 h at 125 °C (Fig. 5). In the same figure it is shown that subsequent solder heat steps at 240 °C and 260 °C did not result into any additional reduction of moisture.

Again, this was checked with more accurate experiments on polyimide foil at 125 °C. Fig. 6 clearly shows that within 1 to 2 min, all moisture is removed. The desorption data provided an additional value of diffusion constant at a higher temperature.

4. Discussion

Absorption and desorption measurement data could be adequately fitted to a well-known diffusion model, e.g. Fick’s law as given in Eq. (1) to extract the parameters needed to simulate the behaviour of the materials as re-passivation layers in the WLCSP. An example of such a fit is shown Fig. 7.

Based on the values of \( D \) determined at three temperatures (30 °C, 85 °C and 125 °C) in the previous section, an Arrhenius plot can be

\[ D_{30} = 3.6 \times 10^{-4} \text{ mm}^2/\text{h}, D_{85} = 8 \times 10^{-4} \text{ mm}^2/\text{h}, E_a = 0.34 \text{ eV} \]

Please cite this article as: K. Rongen, et al., Moisture absorption and desorption in wafer level chip scale packages, Microelectronics Reliability (2015), http://dx.doi.org/10.1016/j.microrel.2015.06.129
made as shown in Fig. 9. The obtained value of the activation energy is 0.34 eV, which is in good agreement with a value of 0.38 eV reported in the literature [1].

The results in the previous section show that a (short) dry bake of WLCSP devices with polyimide re-passivation layers results in rapid desorption of moisture. However, when soaking such dried parts, the moisture level increases very fast and does not get higher than as received parts. Because of the fast desorption rates at moderately high temperatures (150 °C), which is in the order of 1 min, the parts are already “dry” after the pre-heat in a real life soldering profile, so before the onset of the solder heat stage during which temperature can get as high as 240 to 260 °C.

For WLCSPs covered with polyimide repassivation layers, the moisture uptake at 30 °C / 85%RH and 85 °C / 85%RH is similar. This is fully in line with literature [1]. Note that, 30 °C / 85%RH is the floor life condition that is accelerated with 85 °C / 85%RH soak condition for plastic moulded devices.

The material parameters obtained as shown in Fig. 9, can be used to calculate the soaking and drying time of the actual passivation layers, which are much thinner than the foils used for the measurements. As a worst case we can assume that the overall thickness is around 15 μm, the behaviour of which is equivalent to a free standing film twice as thick, so as given in Fig. 4(a) and (b). Drying of such a layer during the pre-heat stage of an actual reflows step, can be estimated to be within about 2–3 min. Therefore, it has been validated that it becomes completely dry during that stage.

5. Conclusions

5.1. Conclusions out of weighing and simulations

Moisture absorption and desorption in PI layers with a thickness of 5 to 10 μm is a matter of hours at 30 °C, and a matter of minutes at 150 °C. Note, that 150 °C is the pre-heat stage in a PCB mounting solder profile. If moisture desorption is completed after pre-heat, the effect of a peak package body temperature of 240 °C and 260 °C during the solder heat stage is irrelevant. Note, that the peak package body temperature depends on volume and thickness in case of plastic moulded devices.

5.2. Consequence for preconditioning of WLCSP

Soaking of WLCSP devices with polyimide re-passivation layers on MSL1, can be performed with a soak condition of 30 °C / 85%RH and a soak time of 24 h. Taking the very fast desorption at elevated temperatures into account it can even be considered to skip the soaking at all.

References