Impact of Solder Pad Size on Solder Joint Reliability in Flip Chip PBGA Packages

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Abstract

A variety of package parameters impact package reliability. One of the parameters that does not get much attention is the variations in package design that are assembly and vendor related. It was shown in this study that the solder pad size plays a big role in solder joint reliability. The difference in solder pad size due to different vendors and processes can affect the reliability considerably. In certain cases, the pad size effect can be so significant that it will override the effect of substrate thickness. Our work indicates that in order to obtain good correlations between predictive engineering results and reliability tests data, this factor should not be ignored. In this paper, finite element analysis was used to study the impact of substrate thickness on solder reliability for flip-chip PBGA (plastic ball grid array) packages. The simulation results were experimentally validated with moiré interferometry. Both numerical and experimental results indicated that better solder reliability could be achieved by using thicker substrate. However, the size of BGA solder pad was found to be crucial to BGA life. In order to achieve higher C5 (controlled collapse chip carrier connection) reliability, larger solder pad is preferred.

Introduction

In flip chip PBGA packages, a predominant failure mode is the fatigue failure of C5 solder joints. Finite element analysis has been successfully used to predict the impact of a variety of package parameters on package life. One of these parameters is the substrate thickness. For a full array flip-chip PBGA package, it was found through both finite element simulation and laser moiré measurement that package life improves as the substrate thickness increases. However, reliability tests on FSRAM packages found best package reliability for the thinnest substrate. This indicates the influence of some other package parameters that are often ignored. In this paper, we have found solder pad size plays a big role in the solder joint reliability. The difference in solder pad size due to assembly and vendor related variation can affect the reliability significantly. In certain cases, the pad size effect will override the effect of substrate thickness. The importance of the pad size effect on solder joint reliability has been empirically seen. This effect was quantified in this paper. Our work indicates that in order to obtain good correlations between predictive engineering results and reliability tests data, this factor should not be ignored.

Problem Definition

In this paper, the package studied was the 0.75mm C5 pitch, 11x15 array FSRAM package. Substrate thickness of 0.1mm, 0.5mm and 1mm were evaluated. Package geometry is shown in Fig.1.

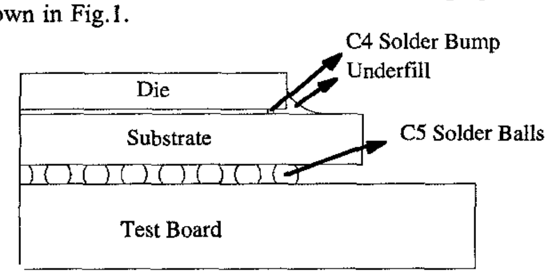

Figure 1 Package Geometry

The dimensions and materials of each component are listed in Table 1. The material properties were obtained from vendors and CINDAS database. [1] Temperature-dependent, elastic-plastic material properties were used for solder material. [2] C5 solder balls are 0.5mm (20mil) in diameter before reflow. The packages were mounted to a FR-4 test board and went through temperature cycles from -40°C to 125°C. Life was predicted based on the characteristic (63.2%) life of packages with 0.5mm BT substrate, 1704 cycles, assuming that it has the same pad size on substrate and board side, 0.350mm / 0.350mm. The Coffin-Manson relationship was used to predict C5 life, [3]

$$N_f = \Theta(\Delta\gamma_p)^\eta \quad (1)$$

where N_f is the number of cycles to failure, $\Delta\gamma_p$ is the plastic strain range, Θ and η are material constants.

Table 1 Package Geometry and Materials

	Size (mm)	Thickness (mm)	Material
Die	10.5x7.0	0.737	Silicon
Substrate	13.5x10.5	1.0, 0.5, or 0.1	FR-4, BT, or Flex
Board		1.62	FR-4
Underfill			Hysol 4527
BGA	0.500 Diameter	0.368	Eutectic solder
Bump	0.125 Diameter	0.1	Eutectic solder

Substrate Thickness Effect On Package Reliability

Finite Element Analysis

Axisymmetric finite element models were built to simulate FSRAM packages. Since solder strain is sensitive to mesh density and quality, submodel was used for the solder joint at the location with maximum solder strain. Packages with 0.1mm, 0.5mm, and 1mm FR-4 substrates were modeled. The C5 ball diameter before reflow was assumed to be 0.5mm. For the standard solder joint, the solder pad diameter is 0.350mm on both substrate side and board side. The predicted life of C5 solder joints are shown in Fig.2 as a function of substrate thickness. It can be seen that for the same substrate material, thicker substrate gives better C5 solder reliability.

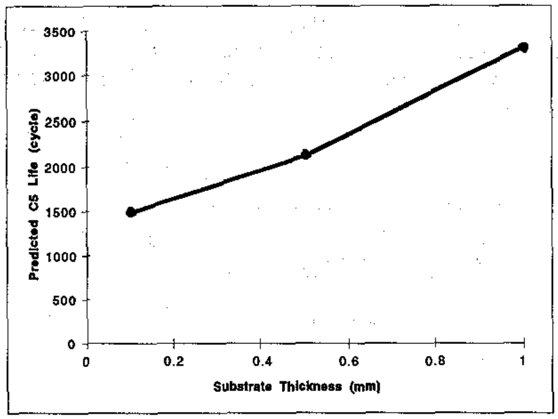

Figure 2 Predicted Substrate Thickness Effect on C5 Reliability with FR-4 Substrate

The substrates used in actual reliability tests are 1mm FR-4, 0.5mm BT, and 0.1mm flex substrate, respectively. Assuming that the solder shape is exactly the same in these packages, the predicted C5 solder fatigue life are shown in Fig. 3. Therefore, for the actual substrates used, we should still see the best solder reliability for the thickest substrate, i.e., 1mm FR-4 substrate performs better than 0.5mm BT substrate, and they both perform better than 0.1mm Flex substrate.

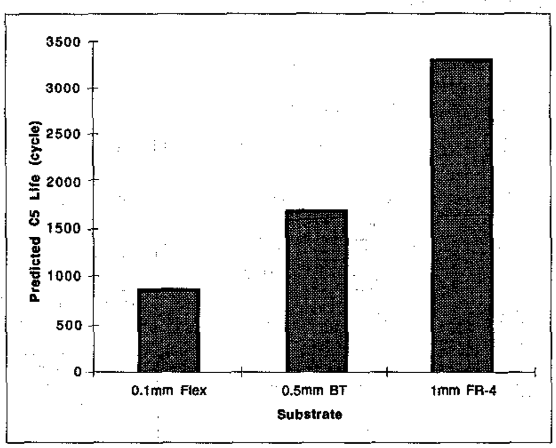

Figure 3 Predicted C5 Reliability for Packages with Substrates Used in Reliability Tests

Moiré Interferometry Validation

The above results from finite element analysis were validated by experimental results. Laser moiré interferometry was used to measure the displacement field of the package cross-section. The horizontal displacement fields of packages with 1mm FR-4 substrate and 0.1mm flex substrate are shown in Fig.4. The resolution is 0.42μm per fringe order. Both packages were cooled down from 85°C to room temperature. There are a lot more horizontal fringe lines in C5 solder balls in the 0.1mm Flex substrate package, indicating higher gradient of displacement field. Therefore the solder balls in packages with thinner substrates are seeing higher strains. They will fail earlier than C5 balls in packages with thicker substrates.

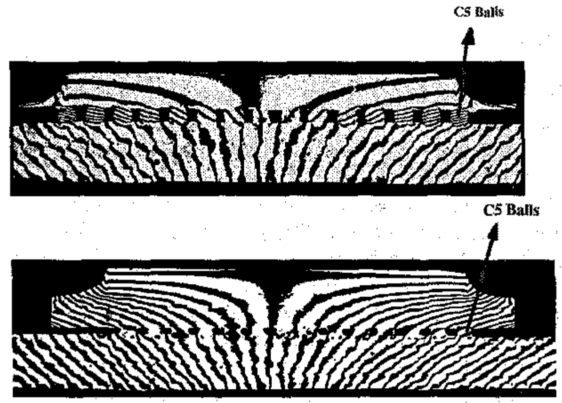

Figure 4 Horizontal (U) Displacement Contours Measured with Moiré Interferometry, ΔT=-60°C

Top: 0.1mm flex substrate; Bottom: 1mm FR-4 substrate

Reliability Tests Data

Existing reliability tests on other Flip-Chip PBGA packages have shown the same trend, i.e., packages with thicker substrate have better performance. As shown in Fig.5, packages with the 1mm (41mil) substrate have much longer solder fatigue life than packages with 0.7mm (27mil) substrate. This agrees very well with the finite element results and experimental data.

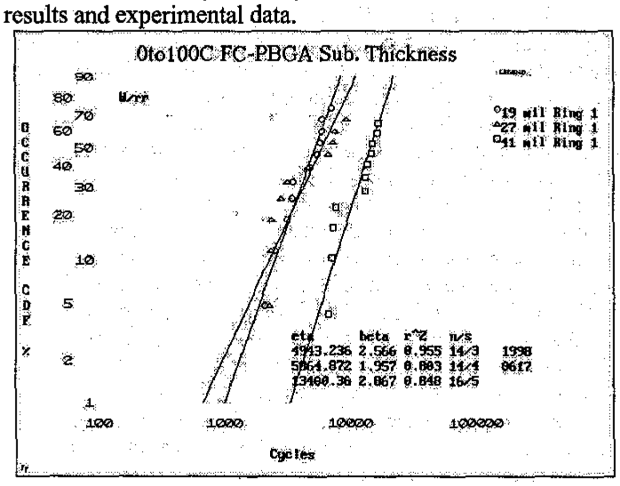

Figure 5 -40 to 125°C Reliability Test Data of FC-PBGA Packages with Varied Substrate Thickness

However, the actual reliability tests conducted on these FSRAM packages support a different conclusion. Despite the finite element prediction and moiré interferometry indication, the reliability test data shows that the longest package life was obtained for packages with 0.1mm flex substrate. The actual life data is shown in Fig.6, along with finite element predictions.

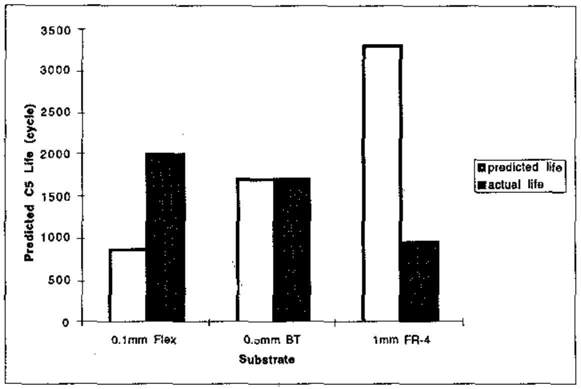

Figure 6 Comparison of Predicted Life and Actual Life of Packages with Different Substrates

The results given by reliability tests were of the opposite trend. However, even though we assumed that solder pad size is the same for the substrate side and board side in all the packages, it was noted that in packages used in reliability tests, some solder pads are much smaller on one side, as shown in Fig.7. In these cases, the C5 ball usually cracked due to fatigue on the side with the smaller solder pad.

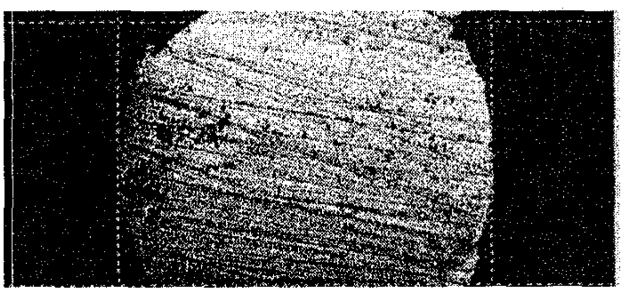

Figure 7 C5 Joint with Smaller Pad on Top

Therefore to explain the discrepancy between the prediction and test data, some assembly and vendor related package variations need to be explored. One of the parameters that were often overlooked is solder pad size.

Solder Pad Size Effect On Package Reliability

Finite Element Parametric Study

The impact of C5 pad size on C5 reliability was examined. Substrates of 0.1, 0.5, and 1mm thickness were studied. The C5 ball diameter was 0.50mm. The combinations of C5 pad size (substrate side pad (mm) / board side pad (mm)) of 0.175/0.350, 0.350/0.350, 0.350/0.175 were studied, as shown in Fig.8.

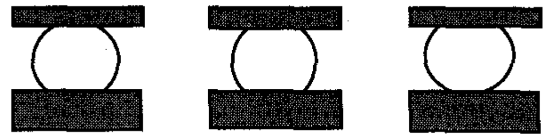

Figure 8 Inverting Substrate/Board Pad Size

(a) 0.175/0.350, (b) 0.350/0.350, (c) 0.350/0.175

When changing solder pad size, the shape of the reflowed solder joints also changed. Caution had to be taken to make sure that solder volume remains constant. Surface evolver tool was used to determine reflowed solder dimensions. [4] The thermal cycle is -40°C to 125°C (15 minute ramps and dwells). Life is predicted based on the life of the package with 0.5mm BT substrate, 1704 cycles, assuming that it has the same pad size on top and bottom, 0.350mm/0.350mm.

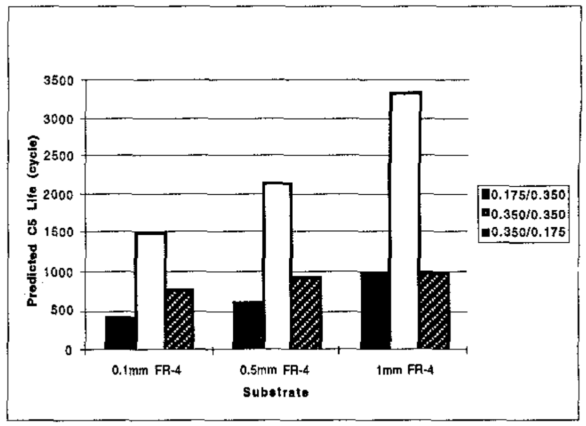

Figure 9 Predicted Effect of Inverting Top/Bottom Pad Size on C5 Life

The C5 reliability is always better in the case with the same pad size on top and bottom, 0.350/0.350, than cases with a reduced pad size on one side, no matter the smaller pad size is on substrate side (0.175/0.350 case) or on board side (0.350/0.175). The predicted characteristic life for different pad size combination is shown in Fig.9. For the cases with different pad size, the C5 joints has better performance when the smaller pad is on the board side rather than the substrate side. Even if 0.350/0.175 C5 ball just has 0.2% longer life than the reversed shape for 1 mm FR-4 substrate, it has ~50% longer life for 0.5mm FR-4 substrate, and ~90% longer life for 0.1mm FR-4 substrate than 0.175/0.350 case.

The combinations of C5 pad size (substrate side pad (mm) / board side pad (mm)) of 0.175/0.350, 0.350/0.350, 0.525/0.350 were also studied, as shown in Fig.10.

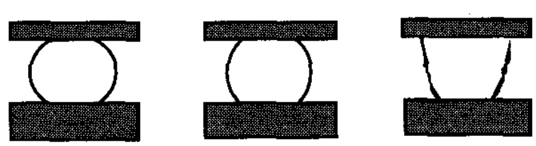

Figure 10 Changing Substrate Pad Size while Keeping Board Pad Size Constant

(a) 0.175/0.350, (b) 0.350/0.350, (c) 0.525/0.350

For packages with FR-4 substrate, when the bottom pad size is fixed at 0.350mm, the C5 reliability increases when the top pad size increases, as shown in Fig.11.

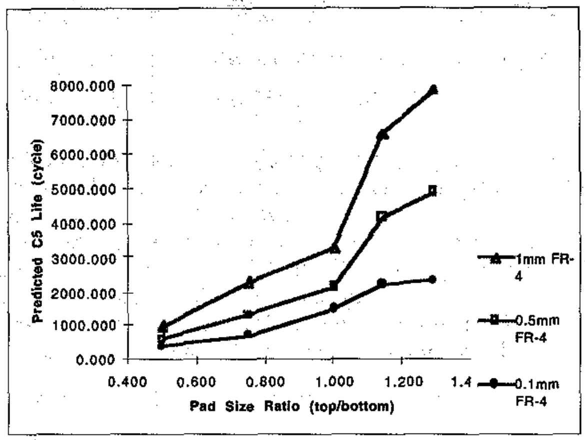

Figure 11 Impact of Top Pad/Bottom Pad Size Ratio on C5 Reliability with FR-4 Substrate

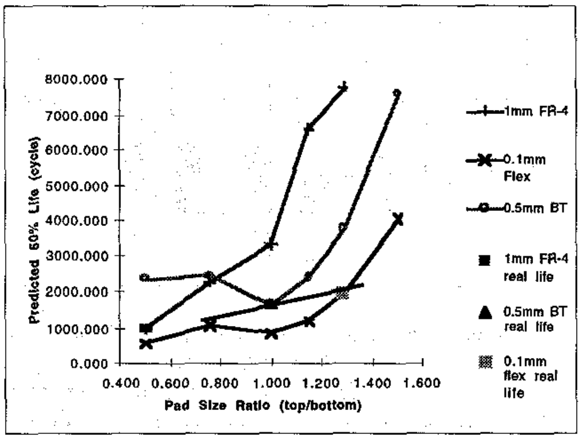

Figure 12 Impact of Pad Size Ratio on C5 Reliability with Actual Substrate

Like the FR-4 substrate, for BT substrate and Flex substrate, while the top pad size is greater than the bottom pad size (0.350mm), the predicted C5 reliability does improve. However, unlike FR-4, when the top pad size is smaller than the bottom pad size, the C5 performance doesn't necessarily have to be worse. The pad size effect on the package reliability with the three substrates used in actual reliability tests is shown in Fig.12.

If the pad size ratio is 0.5 for the 1mm FR-4 substrate, 1.0 for the 0.5mm BT substrate, and 1.28 for the 0.1mm Flex substrate, finite element analysis predicts approximately the same number of package life as the reliability data, i.e., 972 cycles, 1704 cycles, and 2003 cycles. The packages with 0.1mm Flex substrate give the best reliability. Pad size effect has overridden the effect of substrate thickness.

The pad size effect on C5 solder joint reliability was further studied for C5 balls with the same pad size on both substrate and board side. 164 pin FSRAM packages with 0.1mm, 0.5mm, and 1mm FR-4 substrate were studied. The pad sizes studied are 0.25mm, 0.3mm, 0.35mm, and 0.4mm. For each substrate thickness, the C5 reliability increased significantly as the pad size increased, as shown in Fig.13. While for the same pad size, thicker substrate always gives better reliability. Therefore, to optimize the C5 reliability, the largest pad available should be selected. The solder reliability is more sensitive to solder pad size for thicker substrate. It is also more sensitive to substrate thickness for larger solder pad.

Impact of Actual C5 Pad Size on FC-PBGA Package Reliability

The actual diameters of the non solder mask defined solder pads on both the substrate side and board side of the FC-PBGA packages were measured.

As mentioned before, if all the solder balls were of exactly the same size and shape, packages with 1mm FR-4 substrate should have better reliability than packages with 0.5mm BT substrate. However, the reliability tests show that the characteristic (63.2%) life of C5 balls in packages with 1mm FR-4 substrate is lower than that of packages with 0.5mm BT substrate. Our explanation of this discrepancy is solder pad size effect. To validate this explanation, we need to investigate if the actual pad size could give us reversed trend, i.e., better reliability for the thinner substrate.

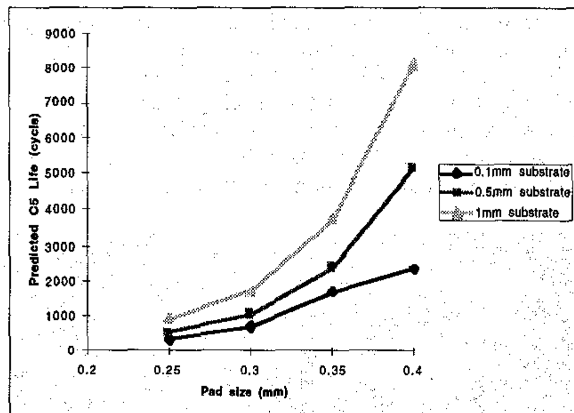

Figure 13 Impact of solder pad size with the same pad size on both substrate and board sides

To evaluate the effect of pad size in the actual packages, we selected different combinations of measured pad size and studied the corresponding package reliability. For packages with 1mm FR-4 substrate, the pad diameter chosen is 0.243mm on the substrate side, 0.232mm on the board side. For packages with 0.5mm BT substrate, the pad diameter is 0.256mm on the substrate side, 0.254mm on the board side. Note that these diameters used in the simulation all fall within the range of actual measurement. For these pad size combinations, the predicted life of packages with 1mm FR-4 substrate will be 25% lower than the packages with 0.5mm BT substrate. Therefore, for the actual packages, the effect of solder pad size could override the effect of substrate thickness. Packages with thinner substrate and larger C5 pad size could end up having better reliability than packages with thicker substrate and smaller C5 pad size.

Conclusions

For flip-chip PBGA packages with full array C5 balls, both finite element analysis and moiré interferometry show that thicker substrate gives better C5 solder reliability. However, the size of C5 solder pad was found to be critical to C5 life as well. Packages with thinner substrate and larger C5 pad size could end up having better reliability than packages with thicker substrate and smaller C5 pad size. It is very important to take C5 pad size into account when we correlate finite element prediction and actual reliability data.

If solder pad on one side is much smaller than the pad on the other side, the C5 ball usually fails due to fatigue on the side with the smaller solder pad. This has been seen in both the reliability tests and finite element simulation. In order to achieve higher C5 reliability, larger solder pad is preferred.

Acknowledgment

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