Vehicle LSI Circuit Package Mounting Technology

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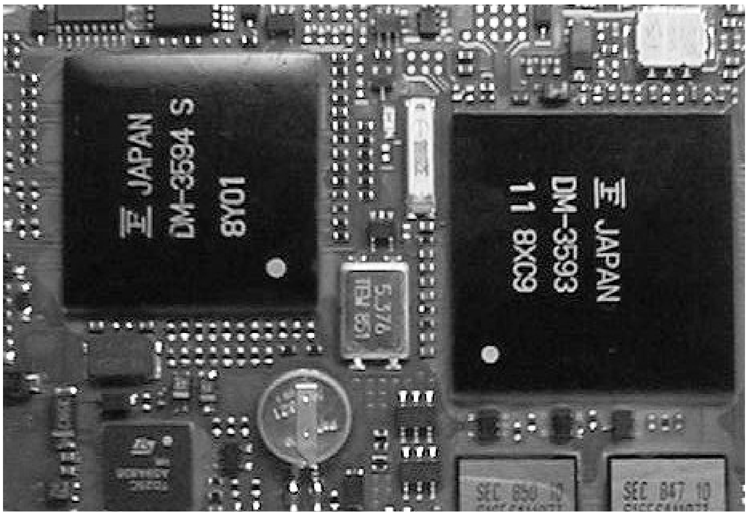

Abstract

In today's automobiles, electronic equipment items such as engine control systems, air bag systems, and navigation systems have become indispensable. The functions of such equipment have also grown more complex and advanced each year. But in order to provide such vehicle electronic equipment with more advanced functions and higher performance while ensuring that they fit in the limited space of an automobile, large-scale integrated (LSI) circuit technology and the high-density mounting technology of such equipment is essential.

This report summarizes the technical issues that must be resolved to attain on-vehicle reliability when mounting semiconductor packages that support such high-density mounting. It also explains design-related considerations, optimization through the use of simulation, and improvements of materials such as soldering paste and Underfil, which are essential for attaining high density and high reliability.

1.Introduction

As evidenced by recent portable telephones and notebook computers, startling advances are being made in electronic equipment as such equipment is being made smaller, lighter, with multiple functions, and with higher performance. Such advances have been made possible by the development of larger-scale and further-integrated LSI (large-scale integrated) circuits; smaller, thinner, and lighter system components; as well as smaller electronic parts, multilayered circuit boards, microwiring, and other features of higher-density mounted circuit boards. The flow of digitization in recent years in particular has given microcomputers, ASICs (application-specific integrated circuits), and other semiconductor devices extremely diverse packaging, including multipin and narrow-pitch forms, for higher performance, more functions, and higher-density mounting. Thus, it has become difficult to attain the initial quality and adequate connection reliability through the use of conventional mounting technology to mount/solder these semiconductor devices.

This report explains the mounting design and the optimization of circuit board, and solder and other materials that are required to attain on-vehicle reliability when mounting semiconductor packages that support such high-density mounting.

2. LSI circuit package evolution and technical issues

2.1 Evolution of LSI circuit package

Figure 1 shows how the form of the LSI circuit package has evolved over time.

The 1980s were years of transition in which there was a shift away from the conventional pin-insertion-type DIP package to the surface-mounted SOP and QFP packages. As mentioned previously, however, with increasing demand for smaller semiconductor devices and an increase in the number of input-output terminals, the pitch between terminals has narrowed in the SOP and QFP packages; and BGA and CSP, whose terminals are arranged in a grid at the bottom of the component, have recently become mainstream LSI circuit packages.

Figure 2 is a photograph of typical LSI circuit packages. From the left are shown a 0.5 mm pitch CSP, 0.8 mm pitch CSP, and 0.4 mm pitch QFP. Each is smaller than a conventional 0.5 mm pitch QFP, having comparative mounting areas of approximately 8%, 18%, and 73%, respectively.

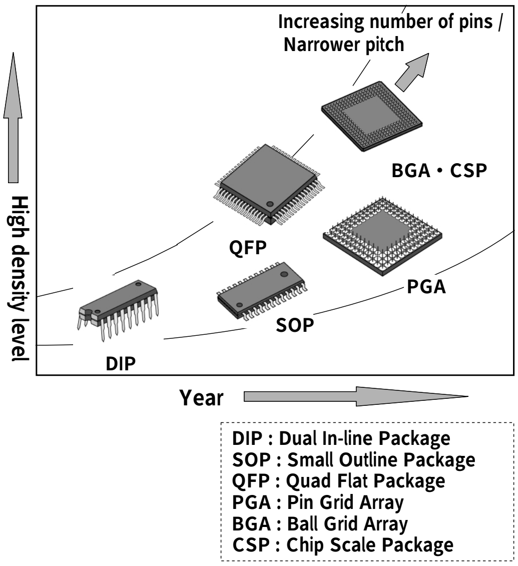

Fig.1 Evolution of LSI circuit packages

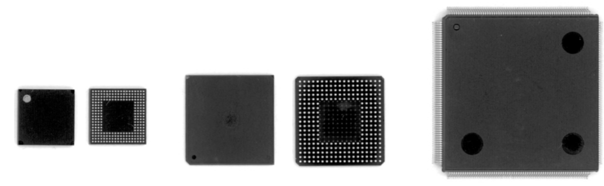

Fig.2 Typical LSI circuit packages

2.2 Mounting-related technical issues

As the terminal pitch of parts becomes microscopic and the area of connection with the printed circuit board becomes smaller, it becomes extremely difficult to attain the initial soldering quality and long-term reliability. Thus, surface mount parts have generally been mounted by means of reflow soldering. But since the soldering land on the circuit board diminishes, it becomes important to utilize soldering paste printing or secure precision mounting of parts in order to achieve the initial soldering quality.

It was thought that the reliability requirements of a conventional semiconductor package would be met if the package was properly soldered. But as the part connection pitch becomes microscopic and the part form approaches the size of the semiconductor chip, a product's long-term reliability can no longer be guaranteed even if soldering is performed under the initial conditions. For example, with the 0.5 mm pitch CSP shown in Figure 2, the solder ball for connecting with the circuit board is φ0.3 mm in diameter. It is connected to the circuit board land by solder. Thus, the connection terminals of the LSI circuit package and circuit board are connected at an extremely close distance. This makes it easy for connection breakage and migration to occur as a result of thermal stress, vibration, humidity, and other effects. For this reason, it is very important to select a circuit board design, circuit board materials, and mounting materials that are appropriate for the parts to be mounted. Furthermore, the optimization of such items is essential in order to maintain long-term, consistent reliability in an environment that is faced by on-vehicle equipment, which is harsher than that is faced by household electrical products.

3. Mounting design

3.1 Attainment of on-vehicle reliability

A particularly crucial element of on-vehicle reliability is thermal shock reliability. Resistance against thermal shock is a central issue in the development of LSI circuit packages as well.

With a conventional QFP package, heat stress caused by differences in linear expansion between the motherboard and package was absorbed by the distortion (deformation) of the gull-wing-shaped terminal as shown in Figure 3. With a BGA package in which the terminals are arranged in a grid at the bottom of the component, differences in linear expansion are directly concentrated in the solder ball as shown in Figure 4; consequently, the reliability of the solder joint is diminished.

According to evaluations up to the present, BGA packages with a terminal-to-terminal pitch of 1.27 mm have a solder ball diameter of φ0.76 mm; thus, sufficient solder joint area is secured and on-vehicle reliability requirements are satisfied. As the terminal-to-terminal pitch narrows, however, reliability is difficult to attain, since a BGA with a 0.8 mm pitch has only 30% of the joint area of one having a 1.27 mm pitch, while a BGA with a 0.5-mm pitch has only about 15% of the area. Moreover, since BGA structure and material vary according to the semiconductor manufacturer, the difference in linear expansion between the motherboard and various packages will vary; consequently, the evaluation results for a certain type of package will not apply to other packages. The generated stress will also vary according to the size of the BGA.

Therefore, since the mounting reliability of a BGA package cannot be determined based on the reliability verification data of the semiconductor manufacturer, and since the assembly manufacturer's mounting design has a great impact, a decision was made to find the optimal combination of package form, motherboard, solder land shape, and solder volume.

Incidentally, the package shown in Figure 4 is generally called BGA if the terminal-to-terminal pitch is 1.0 mm or larger, and CSP if it is less than that. In this report, however, the packages will be uniformly referred to as BGA, based on the form of the terminals.

3.2 Optimal combination

3.2.1 Factors that impact BGA mounting reliability

Figure 5 shows the typical mounting structure of a BGA. Factors that can control the mounting reliability on the assembly side include the following:

1)BGA type: Various structural types have been proposed by LSI circuit manufacturers, but they can be broadly classified according to the material of the interposer that contains the IC chip.

2)Quality of motherboard for mounting BGA

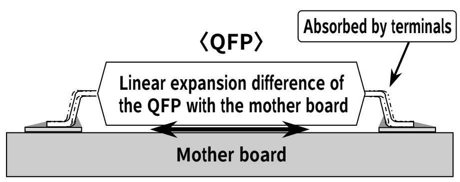

Fig.3 Influence of the thermal stress in QFP mounting

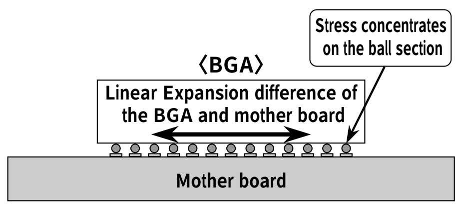

Fig.4 Influence of the thermal stress in BGA mounting

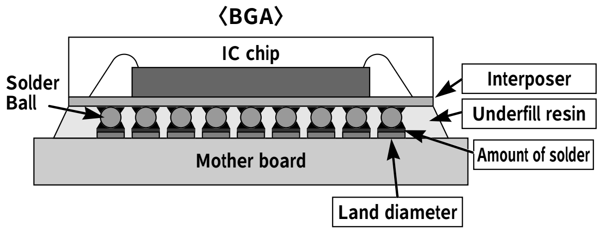

Fig.5 BGA mounting structure

3)Land diameter and solder volume (print mask shape)
4)Existence of underfill resin and quality of material

3.2.2 Results of evaluation of mounting reliability control factors

To study the impact that the aforementioned factors have on mounting reliability, BGA packages were mounted according to the factors and levels shown in Table 1; then the reliability was evaluated.

As part of the evaluation results, significant differences among the levels of each factor were analyzed according to the interposer and based on quality engineering desired specific characteristic values. For example, the factor effect of a ceramic interposer BGA is shown in Figure 6. It became clear that the reliability changed greatly depending on the quality of the motherboard and whether underfill resin existed.

Table 1 Evaluation factors and levels

Factor	Level
Interposer	Ceramic, Polyimide, BT resin
Mother board	FR-4, Low α High Tg board
Land diameter	Large, Small
Solder mask diameter	Large, Small
Underfill resin	Yes, No

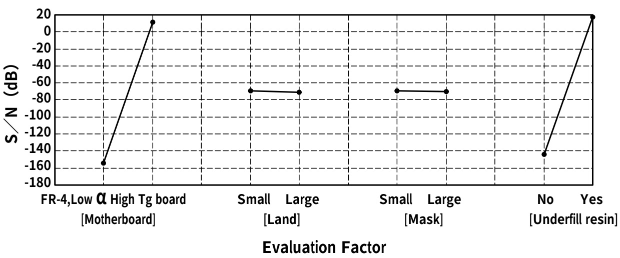

Fig.6 The factor effect figure of ceramic-interposer BGA

Table 2 Differences in significance between evaluation factor levels

Factor	Life trends between factor Levels
Interposer	Ceramic < Polyimide < BT Resin
Mother board	FR-4 < Low α High Tg board
Land diameter	Large=Small
Solder mask diameter	Large=Small
Underfill resin	Yes>No

Table 2 summarizes the life trends between factor levels. The item having the greatest impact was the quality of the BGA interposer material. It was clear that, compared to BGAs of other interposer material, the connection reliability of a ceramic interposer noticeably drops. Actually, however, for each semiconductor manufacturer, there are various types of BGA structures. It is difficult to limit the package form to a single type. For this reason, it is important to find combinations of factors that will satisfy on-vehicle reliability for each type of BGA structure. The optimization of such combinations is an important key to utilizing BGAs successfully.

3.3 Wiring board for BGA mounting

A BGA with a 1.27 mm pitch has wide ball spacing, and can thus be mounted on a general through-hole multilayer printed board. If a BGA has a narrow ball-to-ball pitch, however, wires can no longer be drawn from the terminals, making it impossible to mount on a through-hole multilayer printed board.

Let's look at a BGA with a 0.8 mm pitch as an example. Assuming, as shown in Figure 7, that it is designed such that a single pattern passes between the terminals,

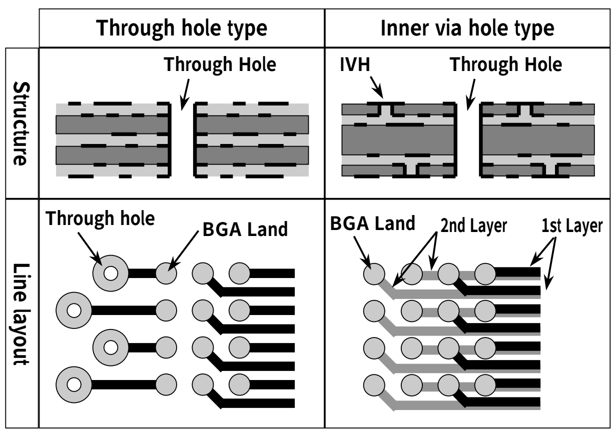

Fig.7 PCB type and wiring condition at BGA

then up to three rows of balls can be pulled to the outside, thus restricting compactness and multipin requirements. And multiple through-holes at the bottom of the BGA make it impossible to fill underfill resin materials.

To examine mounting by using as a target a BGA with a 0.8 mm pitch, a multilayer circuit board with stacked inner via hole (IVH) as shown on the right side of Figure 7 was selected. Using a stacked-IVH multilayer circuit board enables wiring to be pulled through the IVH to the outside from the second layer and it becomes possible to use BGA terminals of up to a four-row grid, combining the first and second layers. And if through-holes are used jointly, a BGA of up to five rows can be used.

3.4 Predicting BGA mounting life using CAE

Factors that influence mounting reliability were mentioned previously. Using actual equipment to evaluate and verify the relationships between the mounting structure and thermal shock life for various BGAs, however, generates a great deal of wasted time and expense. Thus, computer-aided experiment (CAE) was utilized to gain a quantitative understanding of these relationships. To simulate the stress that acts on the BGA mounting structure and to calculate the stress and strain in each part, finite element method (FEM) nonlinear analysis software that takes into account the creep characteristics of the solder was employed.

Figure 8 shows an analytical model that was created based on the condition in which a typical BGA is mounted on a motherboard.

As a result of simulating using such a model, an accumulated strain curve of the thermal shock cycle was obtained as shown on the left side of Figure 9. Using the accumulated distortion of a single cycle as an analytic indicator and then mapping the accumulated distortion of each part gives us the strain distribution diagram shown on the right side of Figure 9. Maximum strain is produced at the base of the solder ball on the interposer side. This matches the location of joint rupture indicated in the actual-equipment evaluation results (Figure 10).

Figure 11 shows a plot of the relationship between the distortion amplitude (when simulating with various combinations) and rupture life (when testing the thermal shock with actual equipment) for two types of BGAs in which the interposer is a polyimide or BT resin. The relationship line of the distortion amplitude and thermal shock life shows a correlation of 94% or more; thus, simulating the mounting structure made it possible to predict the thermal shock life.

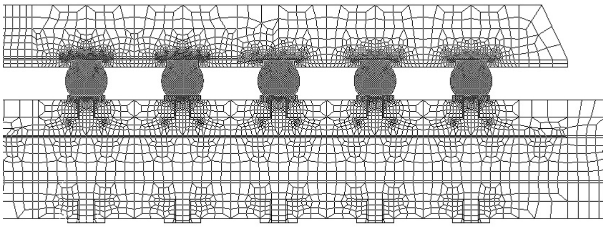

Fig.8 Analytical model of BGA mounting

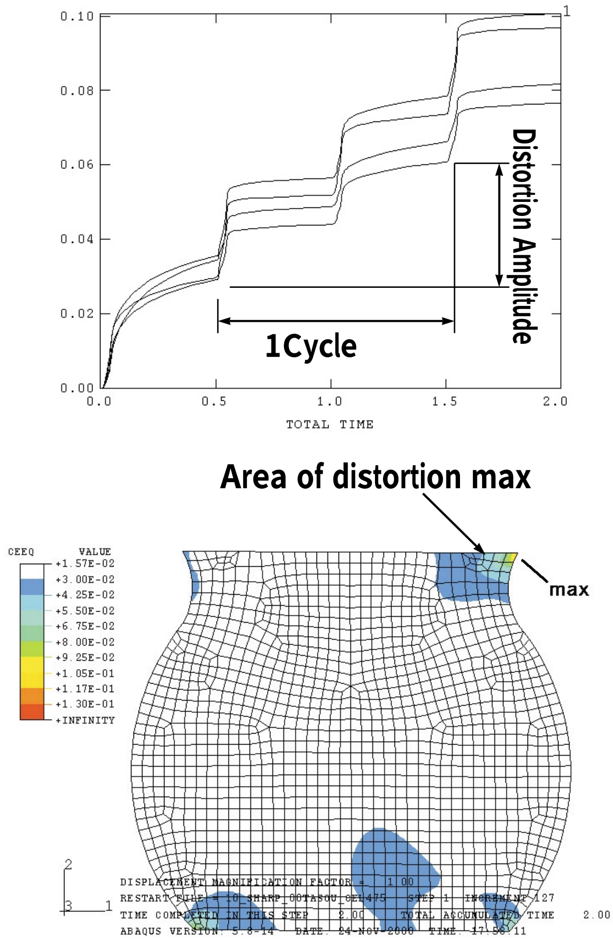

Fig.9 Accumulated strain and analytical result

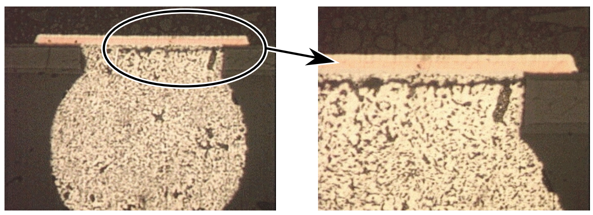

Fig.10 The location of rupture in actual test

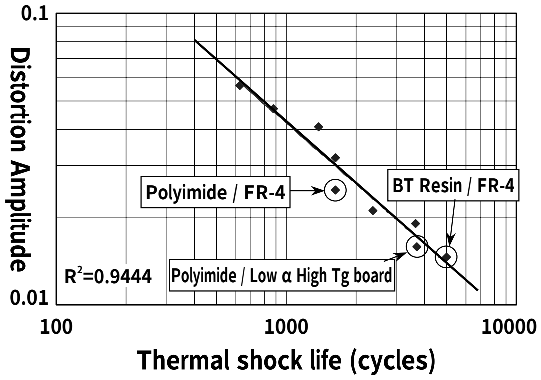

Fig.11 Relation between strain amplitude and the thermal shock life

3.5 Difference in thermal shock life based on BGA internal structure

It is generally thought that the maximum strain in a solder joint occurs at the extreme outside perimeter of the BGA, where the difference in linear expansion between the motherboard and package is most likely to be absorbed. For the polyimide interposer BGA that was evaluated in this study, however, the maximum strain was present in the ball joint on the third row. The internal structure of the BGA used in this study is shown as BGA (A) at the top of Figure 12. The IC chip was affixed directly to the polyimide interposer. The IC chip, whose linear expansion was low, was thought to be the controlling force on the inside of the package; thus, it was thought that the maximum strain was produced near the outside perimeter of the IC chip.

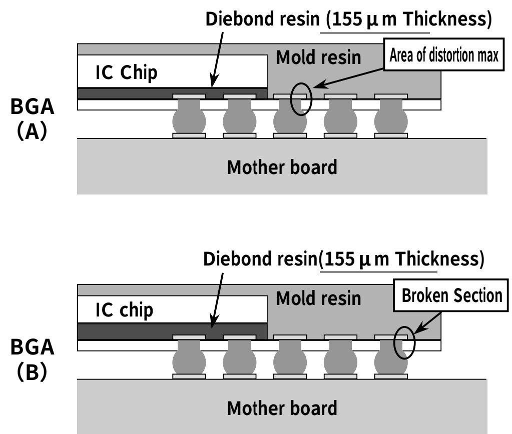

Fig.12 Structure of polyimide-interposer BGA

Similar polyimide interposer BGAs of some LSI circuit manufacturers, however, have a thermal shock life that is equivalent to that of BT resins, and also rupture on the extreme outside perimeter of the BGA. BGA (B) of Figure 12 shows the internal structure of such a BGA. In comparison to BGA (A), there were two large differences: the thickness and quality of the die bonding material that fastens the IC chip to the polyimide interposer. The thickness was 155 μm, which was more than five times the 30 μm thickness; and the material used was a flexible resin. It is thought that the thicker, more flexible diebond material improves the thermal shock life because the effects of the IC chip's low thermal expansion are not transmitted to the polyimide material, thus preserving the polyimide material's original characteristics.

As indicated above, since thermal shock life changes according to the internal structure of the BGA, it is necessary to consider internal structure when selecting the BGA to use.

3.6 Summary

Here is a summary of the achievements that have been obtained from the results thus far.

1)Combinations that can be mounted on a standard FR-4 circuit board and that satisfy on-vehicle reliability requirements were discovered.

2)With CAE the thermal shock life can be predicted from the BGA structure, and new mounting examination periods can be shortened.

3)Combinations that can support even higher reliability targets were discovered.

These achievements will be used during new product development in the future.

For reference, Table 3 shows combinations that meet on-vehicle reliability requirements, summarizing them according to combinations of interposer materials and motherboard materials that have a great effect on on-vehicle reliability.

Table 3 Combinations that meet on-vehicle reliability requirements

	Interposer			
Mother board	Ceramic	Polyimide Type I	Polyimide Type II	BT Resin
FR-4	×	×	○	○
Low α High Tg board	×	○	◎	◎

Polyimide type I is in fig. 12 BGA(A), Type II is in Fig 12 BGA(B)
The symbols in the table show ×:not acceptable ○:acceptable
◎:Acceptable, having margin

4. Mounting materials

Securing mounting reliability requires not only consideration of the design but optimization of the materials to be used. This section will examine some important aspects of two of these materials: soldering paste and underfill resin.

4.1 Soldering paste

4.1.1 Printability

As parts have become more compact and dense, and the terminal-to-terminal pitch has narrowed, the soldering paste print span has also decreased. To secure fine printability, the following actions can be listed:

① Reduction in thickness of metal mask
② Development of microscopic solder particles
③ Improvement of flux composition
④ Smoothening of metal mask's interior surface

Since action 1 reduces the amount of solder, there will be a drop in connection strength, thermal shock resistance, and other aspects of connection reliability. For this reason, improvements were made to 2, 3, and 4.

1) Development of microscopic solder particles

Generally, the size of a metal mask opening is thought to be ideal if three solder particles can be aligned in the thickness strain, and five particles in the width strain. If the thickness strain is larger than this or if the width strain is smaller than this, the solder's capacity to penetrate diminishes.

For the LSI circuit package mounted in this study, the mask opening was set at 190 μm; thus, with a conventional solder particle size of 20-40 μm, the capacity to penetrate diminished and printer blurs and horns were visible. The solder particle size was then changed to 20-38 μm and the powder separation accuracy was improved. This reduced the percentage of 38 μm and larger particles from 5% to 2% or less.

2) Improvement of flux composition

To improve the capacity to penetrate narrow metal mask openings, N-substitution fatty acid amide was added to the flux composition.

Since this substance has no affinity to metal surfaces and other objects having polarity, it acted to reduce adhesion to the metal mask's interior surface when added to the soldering paste. Also, a conventional alcohol solvent was partially replaced by diglycolic ether. The viscosity of this solvent was 8 (mPa.s), which was considerably lower than the 30 (mPa.s) of the conventional alcohol solvent. This reduced the viscosity and adhesiveness of the resin components in the flux, and improved the capacity to penetrate. The proportions of the two solvents, as well as the viscosities and thixotropic ratios, are shown in Figure 13. Since a viscosity of 150 (Pa.s) and thixotropic ratio of 0.6 are considered good with narrow-pitch printing, the diglycolic ether content was set as 25% from the graph.

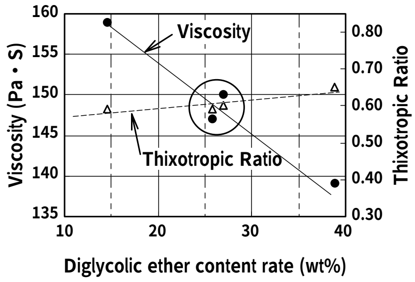

Fig.13 Relation of diglycolic ether content rate, and viscosity/thixotropic ratio

3) Smoothening of metal mask's interior surface

One factor that controls print penetrating capacity during soldering paste printing is the smoothness of the cross section of the metal mask's opening. With conventional methods, such as etching, additive processing, and laser processing, satisfactory smoothness could not be obtained. But when a resin coating was applied to the metal mask opening, the surface roughness was reduced from 3.0 μm to 0.5 μm.

Figure 14 shows the appearance after solder printing, both before and after the aforementioned improvements were made. As a result of the improvements, the usual blurring and projections are absent and a uniform print form has been obtained.

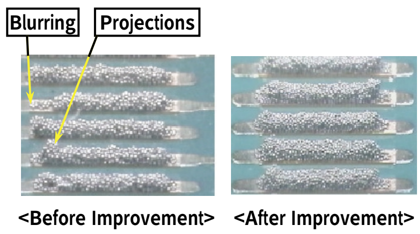

Fig.14 Appearance of solder paste after printing

4.1.2 Insulation reliability

In addition to printability, an important characteristic that is needed to achieve a narrow pitch between part terminals is insulation reliability. For a long time, our company has used a nonwashing method that included N_2 reflow using low-activity soldering paste. And to accommodate the vehicle environment, we developed a soldering paste that is reliable against condensation and ensures that, after soldering, the flux residue film will not crack, even after thermal shock testing. We aimed with this narrow-pitch-printing soldering paste as well to improve printability and insulation reliability, and particularly to prevent the flux residue film from cracking after thermal shock testing.

Table 4 Flux composition table

Classification	Element	Samp(1)	Samp(2)	Samp(3)
Solid	Resin	30	31.7	31.8
	Crack prevention resin (containing quantity %)	10.8 (26.5)	10.6 (25.0)	11. 3 (26.0)
	Thixotropic agent	3.2	3.0	3.8
	Activator, Additions	1.9	1.9	1.9
Solvent	Alcohol type	54.1	39.2	38.3
	Diglycolic ether type	0	13.6	12.8

Linear expansion of the flux itself (particularly contraction when the temperature is low) contributes greatly to cracking of the flux residue film after thermal shock. For this reason, the authors investigated the rate of flux contraction as well as the rate of occurrence of flux residue cracking caused by the presence/absence of N-substitution fatty acid amide added to improve printability.

As shown in Figure 15, the N-substitution fatty acid amide caused the rate of contraction to increase from 33 ppm to 107 ppm, and the residue cracking rate to increase from 0% to 51.6%. It became clear that insulation reliability requirements could not be satisfied. Thus, with the aim of achieving both printability and insulation reliability, the N-substitution fatty acid amide was removed from the flux composition, and the component ratios of the solvents and resins other than this were optimized.

Table 4 is a composition table of the materials that were examined, while Figure 16 shows a radar chart of the experiment results as well as a photograph of the residue's condition following thermal shock.

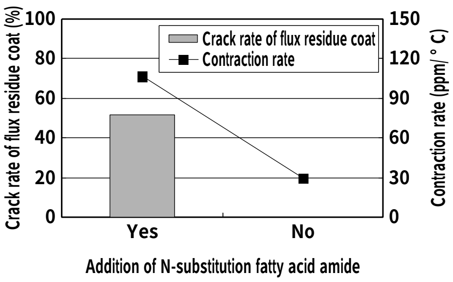

Fig.15 Influence by addition of N-substitution fatty acid amide

From the results of the experiment, the following became clear:

1) The amount of residue crack control resin that is added to the resin should be at least 26%.
2) The amount of thixotropic agent that is added does not contribute to residue cracking.
3) Diglycolic ether solvents do not contribute to residue cracking.
4) The amount of solder can be stabilized by adding the same solvent.

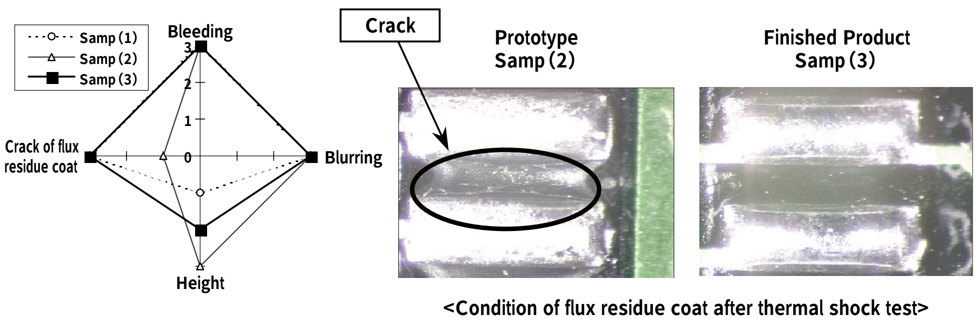

Fig.16 Test results about the flux element

5) Narrow-pitch printability can be achieved even without using N-substitution fatty acid amide.

Samp (3) became the final finished product. For reference, Figures 17 and 18 show the results of insulation resistance testing and low-temperature recovery testing using this soldering paste. It attains reliability that is equivalent to the moisture-proof soldering paste currently being applied to on-vehicle products.

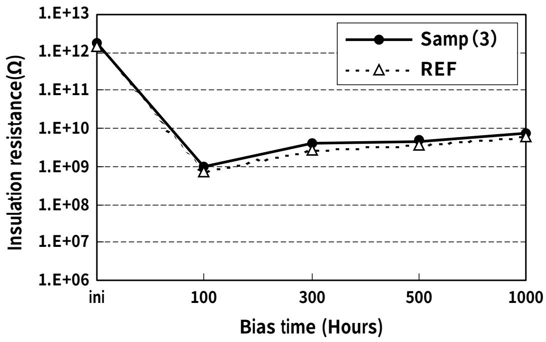

Fig.17 Results of insulation resistance testing

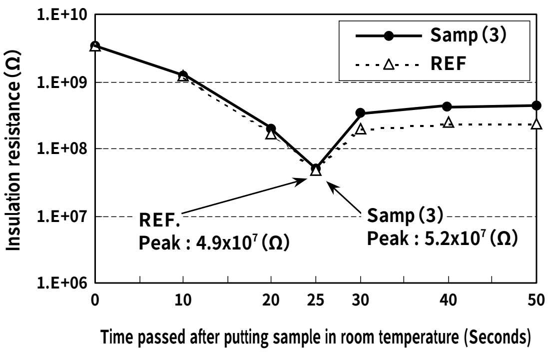

Fig.18 Results of low-temperature regression testing

4.2 Underfill resin

4.2.1 Requirement for underfill resin

The third section of this report explained the large impact that underfill resin had on mounting reliability. Normally when a BGA is mounted on a mother board, heat stress and/or mechanical stress concentrates in the soldered areas. To reinforce these joints and relieve the generated stress, a resin called underfill is added between the mother board on which the BGA is mounted and soldered and interposer as shown in Figure 5.

4.2.2 Points to remember when selecting underfill resin

Underfill resin is inserted into the extremely narrow gap between the mother board and interposer. It must adhere to each of the materials, absorb differences in thermal expansion, and ensure insulation reliability. For this purpose, the selected underfill resin should meet the following

principal requirements:

1) Its glass transition point should be higher than the maximum temperature required for reliability.

2) Its coefficient of linear expansion should be similar to that of the constituent materials in the joint and surrounding areas.

3) Its water absorption and impurities content should be minimal.

4) It should have superior filling performance and its hardening conditions should comply with the heat resistance specifications of the other mounted parts.

Taking these prerequisites into consideration, the authors selected and evaluated a commercially available epoxy thermosetting-type underfill resin.

4.2.3 Evaluation of reliability

The authors actually mounted BGA packages onto mother boards and investigated the change in reliability that occurred when underfill resin was or was not inserted. First, Figure 19 shows the results of thermal shock testing. Products to which underfill resin was added showed a rate of improvement in connection reliability that was approximately three times that of products to which underfill resin was not added. It confirmed that the underfill resin was effective in relieving stress in the solder joints. Next, Figure 20 shows the results of high-temperature high-humidity electric bias testing. From the results it is clear that the insulation reliability of the products to which underfill resin was added dropped to approximately one-fourth that of the underfill resin-free products; moreover, the pattern spacing could not be narrowed. In order to use underfill resin, improvement in this area is essential.

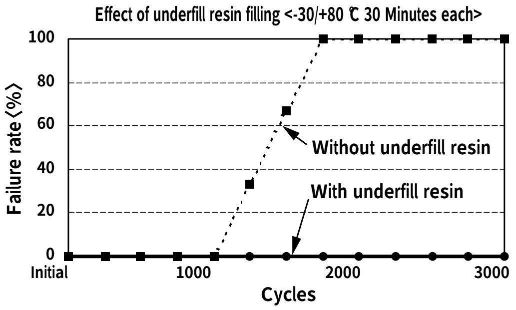

Fig.19 Results of thermal shock testing

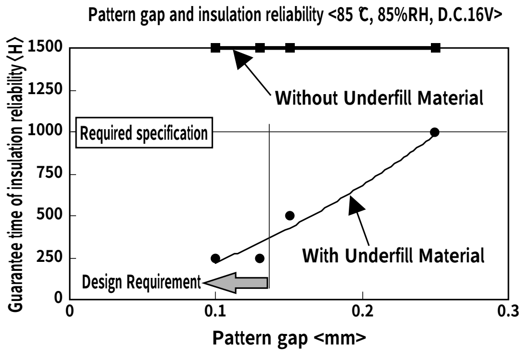

Fig.20 Results of high-temperature and high-humidity bias testing

4.2.4 Improvement of underfill resin insulation reliability

It is conceivable that the drop in insulation reliability that occurred with the addition of underfill resin was due to a couple of factors: insulation deterioration in the underfill resin itself, and moisture penetration into the solder joint. A decision was made to improve these areas, which are summarized below.

① Water absorption high → Drop in volume resistance
② Impurities content high → Insulation deterioration from impurity ions
③ Filling performance poor → Entry of moisture into interior via gaps
④ Adhesion poor → Entry of moisture between electrodes

For the underfill resin, a filler is normally added to an epoxy resin. To improve ①, the high-absorption resin component can be decreased and the filler content increased. Also, increasing the filler content decreases the coefficient of line expansion. Therefore the reliability of thermal shock will be improved. If, however, filler is added to the currently utilized resin component by an amount that is 50% or more by weight, the viscosity of the underfill resin will increase and the fluidity will decrease, worsening the filling performance. Furthermore, since the resin component will decrease, the adhesion will also diminish. To improve ②, the chlorine content of the resin can be decreased, which will restrict the movement of ion impurities. For ③, since the proportions of the resin component and filler have a large effect as previously mentioned, the authors determined an optimal filler content while maintaining a balance between the resin water absorptivity and viscosity change as shown in Figure 21. Finally, to improve ④, the basic characteristics of the resin itself were improved and the strength of the adhesive bonding on the mother board and interposer surfaces was improved.

As a result of these improvements, an underfill resin was successfully developed for use with 0.8 mm pitch CSPs and 0.5 mm pitch CSPs. For power circuits and other areas in which high voltage is applied, however, further improvements are being made because satisfactory reliability has still not been attained.

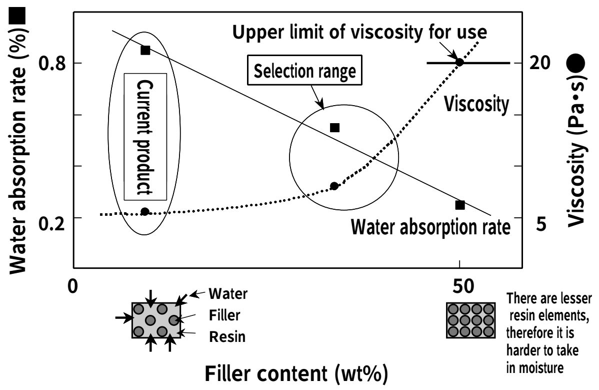

Fig.21 Relation between filler content and water absorptivity/Viscosity

5. Conclusion

This report explained mounting technology to be utilized to accommodate the development of compact, high-density LSI circuit packages. The development of smaller and lighter electronic equipment, including mobile and personal devices, is expected to continue to accelerate. These advances are expected to draw the automobile electronics industry into viewing the adoption of such new LSI circuit packages as indispensable.

The key to ensuring that a product functions and materializes in the future is to acquire a mastery of these new LSI circuit packages while securing their reliability. Hopefully, by utilizing simulation as introduced in this report and by developing new materials, we will continue to develop highly reliable products that provide even higher performance.

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