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A REVIEW OF BALL GRID ARRAYS FOR ELECTRONIC ASSEMBLY

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technology to be adopted as is widely used today.

This paper describes BGA technology and the types of package available, then examines the processing methods involved and reliability issues.

Keywords

Interconnection, electronics packaging, area array interconnect, ball grid array, soldering, reliability.

Introduction

In electronic packaging of silicon die, the best package is considered to be no package. The package, by way of its size and the length of interconnect leads takes up valuable substrate space while introducing timing delays, increasing cost and introducing potential defects. However, packaging of bare die gives these easily damaged devices a certain degree of mechanical and environmental protection. The first silicon chips were packaged in TO can headers that were connected with wirebonds from the top of the die to glass to metal lead through seals, in the 1960's. The package allowed the smaller dimensions of the chip to be connected to the larger features on the PCB. The TO packages allowed the die to be hermetically packaged. As the die complexity increased, the number of I/Os increased, requiring larger packages. For larger die, the cost of hermetically packaging them can be quite considerable. In a move away from hermetic packages, the first plastic packages, where the die was attached to an internal lead frame and encapsulated with an epoxy resin after wire bonding, appeared in the 70's. The plastic package allowed robust devices to be manufactured at a lower cost. These parts, at the time, were considered suitable for the

commercial market only, not the military sector. The first generation plastic packages were coarse pitch devices, 0.75mm, that were mounted through holes in the PCB. As system speeds and functional complexity increased, the requirement to shorten the distance between the electronic circuitry resulted in smaller packages, and higher density substrates to be introduced in the early 1980's, Fig.1. Surface mount components with lead pitches of 0.5mm were introduced around this time.

The problem that some surface mount components, such as quad flat packs (QFPs) have, is the pitch requirements to connect the peripheral I/Os. As the number of I/Os increase, the pitch must be reduced to accommodate the number of pins that the package has. I/O counts have increased, and component lead pitches have been reduced from 0.5mm to 0.3mm, in some cases. The leads can be easily damaged, during transit and assembly of the component to the PCB. The assembly of these components to PCBs must also be carefully controlled.

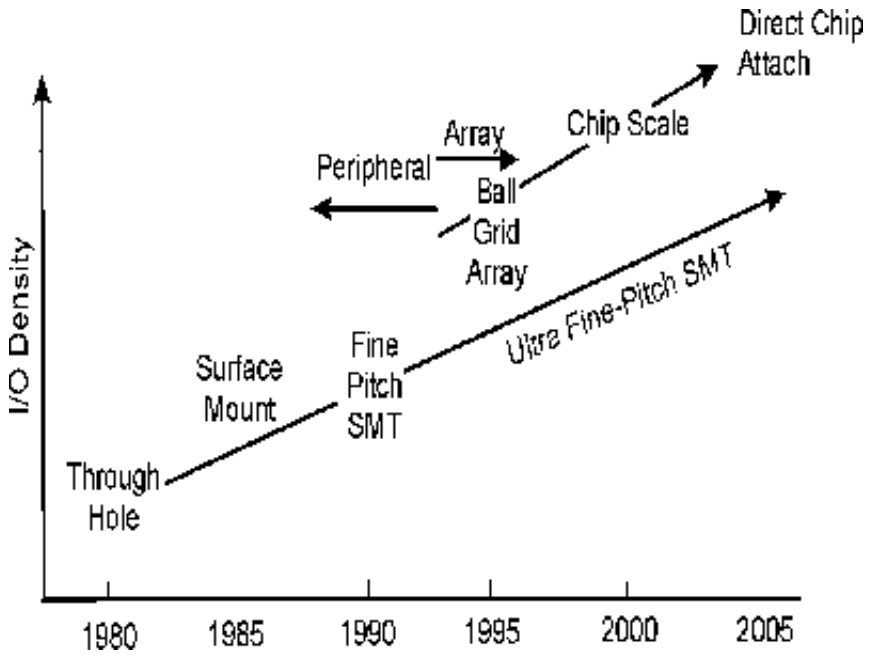

Fig. 1. Package to board interconnection density trends (Courtesy of Motorola) [1]

The development of the ball grid array (BGA), has allowed area array interconnects to be made, removing the problems associated with fine pitch peripheral leads. BGA technologies offer alternative solutions to high density interconnect requirements, using an area array of solder ball connections that can provide packages from 250 to 1,089 I/Os in the same area as a 208 pin QFP. The pitch change, to 1.27mm has alleviated the problems associated with 0.3mm QFPs but added a further complication. Multi-level substrates, required to allow the I/Os to fan out from the device, are now a prerequisite and more refined inspection techniques to look at the hidden solder joint are needed. Despite this, BGA assemblies are rapidly gaining favour as the packaging choice for high I/O devices that require improved electrical connectivity.

BGA Package types

BGA packages consist of an array of solder balls that are attached to the bottom side of the package body or carrier [2], and are available in four main types, as shown in the Table. Two further variants of this packaging technology, of which there are others, are the micro ball grid array (µBGA) and the 'Slightly Larger than IC Carrier' (SLICC) package.

Table BGA types

BGA Type		Construction Details
PBGA	Plastic Ball Grid Array	Organic laminate substrate Low cost
CBGA	Ceramic Ball Grid Array	Co-fired ceramic substrate Good electrical/thermal properties
CCGA	Ceramic Column Grid Array	More compliant joint for high temp. and high power applications
TBGA	Tape Ball Grid Array	TAB-like tape package carrier Good fatigue life

Solder ball attach

There are a number of alternative ways in which the solder balls are attached to the carrier of the ball grid array package. Two of the predominant are i) placing a preformed solid core solder ball into a soft solder already on the carrier or ii) printing a solder paste and reflowing it into a ball.

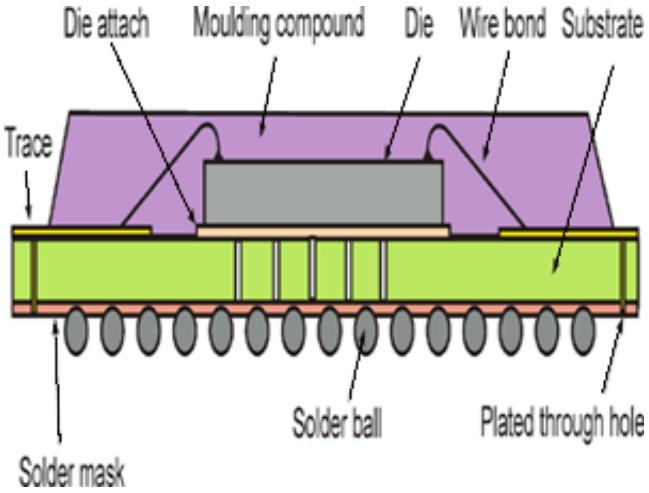

Fig. 2. Plastic ball grid array (PBGA) [3]

Plastic ball grid arrays

Plastic Ball Grid Arrays (PBGAs), sometimes referred to as OMPACs (Over Moulded Plastic Array Carriers) are the most common type of BGA package, Fig.2. The PBGA carrier is made of a PCB material, such as FR4 or BT resin. The die is typically wire bonded to the top surface of the PCB carrier and then overmoulded with a plastic (epoxy based).

The terminations on plastic devices are solder balls, approximately 0.5 to 0.7mm in diameter, attached to the bottom side of the PCB carrier. They are manufactured from tin-lead eutectic (63Sn37Pb) or tin-lead-silver alloy (62Sn36Pb2Ag). Balls may also be produced by liquid solder dispense, or by solder paste print followed by reflow.

Ceramic ball grid arrays

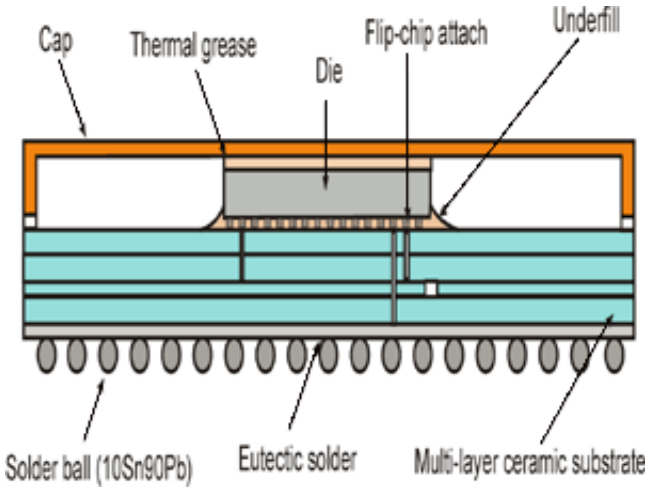

Fig. 3. Ceramic ball grid array (CBGA) [3]

Ceramic Ball Grid Arrays (CBGAs), also referred to as SBCs (Solder Ball Carriers), are a second type of BGA package. The CBGA consists of a die attached to the top surface of a ceramic multilayer carrier, Fig.3. The die can be wire bonded with the active side up or attached with the active side down in a flip-chip configuration. After attachment, the die is encapsulated for improved reliability and mechanical protection.

Ceramic packages use high temperature (solid core) solder balls (90Pb10Sn), on the bottom

side of the carrier, that are reflowed using a eutectic or close-eutectic tin-lead or tin-lead-silver paste. The solder balls are of the order of 0.8mm diameter. The high temperature ball does not melt in the reflow, and thus gives a fixed height stand-off (controlled collapse connection).

Ceramic column grid arrays

Ceramic Column Grid Arrays (CCGAs) are the alternative to CBGAs for ceramic body sizes above 32mm [2] [3]. Instead of mounting solder balls on the bottom side of the ceramic carrier, an array of high temperature 90Pb10Sn solder columns is attached. The column diameters are nominally 0.5mm and are 1.75mm tall. These columns increase the stand-off height and give greater reliability [4] in thermal cycle environments, however, few production applications exist at present for CCGA packages.

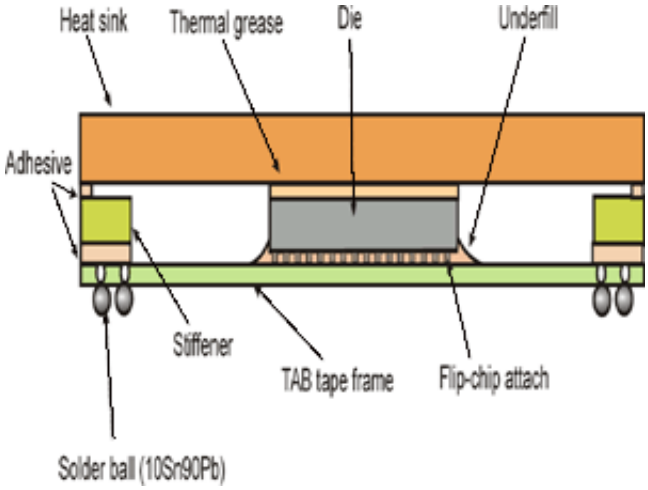

Fig. 4. Tape ball grid array (TBGA) [3]

Tape ball grid arrays

Tape Ball Grid Arrays (TBGAs) are a relatively new type of BGA package, and are being developed by companies such as 3M [5]. The TBGA consists of a die attached to a carrier, copper/polyimide flexible circuit or tape, that has a metal layer either side, see Fig.4. The top metal layer of the tape is a uniform ground plane and the bottom consists of copper lines which will connect the die to the array of solder balls. Wire bonding, solder reflow or

thermo-compression/thermosonic inner lead bonding can be used to attach the die to the copper lines. After attachment the die is encapsulated for protection.

Solder balls are individually attached to the other end of the copper line with a microwelding process similar to wire bonding. The solder balls are 90Pb10Sn and are approximately 0.8mm in diameter.

Area array formats

There are three area array formats that are commonly used for BGA technologies, full arrays, perimeter and partial or modified arrays [6]. Full area arrays can be readily used with PBGA, CBGA and CCGAs. Partial or modified area arrays can be used with PBGA, CBGA, CCGAs and TPGAs. For TPGAs, this array structure is required because solder balls cannot be attached to the centre of the package where the die is located.

Partial area array formats are being adopted due to the concern of stress being applied to the die, where solder balls reside under the silicon. These stresses arise because of the CTE mismatches between the materials used in the construction of the BGA. If a ball is placed near the edge of the silicon die, under thermal loading the die could either delaminate from the carrier or crack due to the resultant high stresses.

Advantages and disadvantages of BGA technologies

The BGA technology offers significant size benefits over conventional surface mount packages. For example, a 1.27mm pitch area array package can accommodate 350 I/Os on a 25mm package, compared to 304 I/Os on a 40mm QFP. The BGA device is also considerably more robust than a comparable QFP, as the conventional package's leads require both accurate placement and tight lead to lead coplanarity. JEDEC [7] lead to lead coplanarity

specifications for BGAs are half as tight as for QFPs, and the placement tolerances required are only a quarter as stringent. Current JEDEC registered footprints for BGAs are on 1.0, 1.27 and 1.5mm pitches; 1.27 and 1.5mm pitch devices are currently being introduced to replace QFPs with pitches of 0.4 to 0.5mm [8]. Improved handling and placement with respect to surface mount components that have smaller than 0.5mm pitches is a major benefit.

Considerable self alignment potential exists for BGA assemblies [9], where realignment of a component misplaced by up to 50% can occur. Assembly yields for BGA devices are widely reported to be much higher than for peripheral leaded packages with equivalent I/O counts. Both Motorola and Compaq have reported zero-defect ppm yields in fully automated assembly of 160 and 225 I/O 1.27mm pitch BGA components. Equivalent defect yields for fine pitch QFP devices are reported to be between 500 and 1000ppm [10].

The in-circuit performance of BGAs also offers advantages in both thermal and electrical management. The improved electrical characteristics of BGA are due to the reduced distance between the component termination and the silicon die. This allows more rapid inter-device communication by reducing parasitic inductance, resistance and capacitance. Thermal performance advantages come from direct connection to the substrate via the solder ball, or through thermal vias directly to the base of the die. Even greater thermal capacity can be provided by utilising a 'chip down' or 'cavity down' ball grid array [11,12]. These components place the die face down, and bond it directly to a heatsink on the top of the package. These thermal and electrical advantages provide both design and assembly advantages over current fine-pitch technology.

One potential electrical disadvantage is that, as with any area-leaded device, the BGA will present a wide distribution of inductances. However, for BGA packages, the actual

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inductance values are lower than those of many other surface mount packages. Two thirds of the leads of a 225 pin plastic BGA package, for example, will have inductance of less than 6nH [13].

As with other area array packages, BGAs present routing difficulties. Several methods of easing routing restrictions are being considered, including using staggered pitches and depopulating the centre of the package (perimeter array). For any high I/O density application using BGA packages, it will be necessary to use multi-layer substrates. However, a limiting factor for BGA use, as perceived by electronics manufacturers, is likely to be the lack of solder joint visibility. The joints are hidden beneath the component and cannot be visually inspected using standard optical microscopes.

Assembly of BGAs

Solder dispense

There are a number of deposition techniques that could be used to attach the BGA to the substrate, that include syringe deposition or printing:

Syringe deposition

Localised deposition of solder paste in the form of dots, circles or lines can be achieved by depositing controlled amounts through a syringe. The syringe is attached to a head that has x and y axis movement and may also have a height sense feature. The correct amount of material can be dispensed by applying a positive air pressure onto the plunger for a known time through a known needle bore. The viscosity and thixotropy of the material must be controlled so that the material flows easily from the syringe, but will not slump after

application.

This technique could be used to deposit a series of dots of solder on to the substrate prior to component attach. This process is very slow and would not be suited to high volume production. However, it has the potential for depositing solder paste during rework.

Stencil printing

Stencil printing allows solder paste to be deposited on large areas of the substrate in one operation. A stencil consists of a thin metal foil with apertures cut in it. The aperture through which the material passes can be etched, laser cut or electroformed. Material is deposited through apertures in the stencil when the squeegee traverse's the print area in contact with the top surface, dragging ahead of it the material to be printed. Stencil printing of solder paste, into which the BGA is subsequently placed, is applicable to high volume production.

Solder jetting

There are alternative solder deposition techniques, such as solder jet printing, that have the potential to be used in area array attach. In a manner similar to laser jet printing of inks, molten solder can be precisely jetted on to a substrate, or component, to form a solder deposit.

Flux only attachment

Flux-only reflow is possible where a tin-lead eutectic or close alloy is used (as in plastic BGA components). Either flux can be deposited on the substrate or the BGA can be flux dipped prior to attachment. The flux will remove any surface oxides present and also holds the BGA

in place prior to reflow. An inert gas process is usually required for flux-only reflow to be successful.

Pre-assembly inspection

There are a number of reasons why a BGA joint may not be formed upon reflow of the solder ball. Common causes of poor solder joints include insufficient solder paste on the PCB or missing/deformed balls on the component. The solder paste deposited on the substrate can be readily inspected after printing, using modern production line printers equipped with measurement systems or by using off-line measurement systems. The heights of the deposits are monitored using laser measurements, while the position and size of the deposits can be optically verified. Missing solder paste deposits can lead to open joints upon reflow as the solder ball on the component will not have been wetted.

BGA component inspection, prior to placement, is recommended - a process that is routinely carried out in SMT assembly. This inspection step must be capable of identifying whether the solder balls are present or missing. It must also be capable of determining if the size and shape of the balls are consistent. A missing ball should be easy to detect but inspection of components for uniformity of ball shape can be difficult. This is due to the high reflectivity of the solder surface.

Component placement

Component placement can be accomplished with standard placement machines as they can easily handle BGA components. Good component alignment can be achieved using the package edges and fiducial marks on the boards as location guides for the placement machines vision systems. The self-aligning properties of the solder ball joints means that

placement tolerances of up to 40-50% can be accommodated.

Solder reflow

There are a number of solder reflow processes capable of reflowing the solder ball joints of a BGA package. Current SMT reflow processes use either IR or convection furnaces to reflow the solder joints. The solder reflow profiles currently used for SMT assembly are readily adaptable for BGA assembly, however the chosen assembly profile would need to be optimised for the individual assembly process. It is conceivable that BGA components only, or a mix of component technologies, could be reflowed, requiring further tuning of the reflow process. Alternative reflow processes, such as a modified vapour phase reflow could also be used for BGA assembly.

At present most PBGA packages are moisture sensitive, and pop-corning (see later) of these packages during reflow could occur. Work is being done to reduce or eliminate this sensitivity, but care must be taken to ensure 'the time out of bag' limits are not compromised. Normally the PBGA components are sealed in bags to minimise the exposure to the air, thereby reducing their chance of absorbing water vapour.

Solder paste application, the design of lands and accurate component placement are key factors in achieving low ppm rejects rates during assembly. There must be sufficient solder paste in the correct area to allow good BGA assembly. The lack of solder paste could lead to a missing solder joint. Too much solder paste or inaccurate printing could lead to electrical shorts. Alternative formats for the pads onto which the solder paste is printed have been proposed to make joint inspection easier later [14].

As the solder joint is hidden from view, the prospects of how to clean the assembly must be

assessed. There are a number of options that include reflow of solder ball in an inert (nitrogen) atmosphere. This does not require additional solder paste and therefore no flux residue will be present. Conversely using no-clean flux materials should also leave a minimum of residue.

Reliability concerns and failure modes of BGA packages

BGAs offer many advantages over conventional large area surface mount packages that can include: low profile, small foot print, high circuit density, increased circuit speed and improved component handleability. However these advantages must be weighed against the potential problems associated with BGAs: how to effectively mount these components to achieve a reliable performance.

Pad design

Choice of design of the substrate can have a high impact on the reliability of the BGA assembly. The geometry of the solder pad to which the BGA is assembled can be particularly critical [15]. A solder resist mask can induce a point of high stress in the ball, resulting in a cracked joint. The worst case scenario would be that the crack propagates 360° around the ball causing electrical failure.

The initial concept of BGA components was to use larger balls (760 µm) to allow I/O counts of a few hundred to be easily attached to a substrate. This meant that although the PCB required more layers and interconnect vias than previously used for SMT applications, to allow electrical connections to be made, the vias were still able to be placed away from the solder joint. As the pitch of next generation BGAs drops to accommodate the increases in

the I/O's, there is now a need to place the via in the pad in some instances [16]. This can result in a number of assembly problems and could cause potential reliability problems as well. The assembly problems can include solder wicking into the via. This would reduce the volume of solder available to complete the joint and could result in ball collapse. To counteract this, either solder paste will have to be forced into the vias or the vias will have to be plugged. The main issue then is whether the via in pad is designed to be through hole or blind.

Movement during/after reflow

Some surface mount components are prone to movement after reflow if dislodged, or disturbed by conveyor movement before the solder has solidified. BGA components are commonly manufactured using the alloy 62Sn36Pb2Ag which has a melting range (rather than the eutectic 63Sn37Pb). This solidification range means that there is a period during which the alloy is partially molten, and in which the component might be displaced. Tests indicate that an average force of 1 gram per solder ball is required to lift a BGA away from a package when the solder is molten [17]; this suggests that BGA packages should be resistant to any gross displacement due to mechanical vibration after reflow.

Popcorning

Plastic BGA packages can suffer from failures due to the 'popcorn' effect. This arises where moisture is absorbed between the substrate and the overmoulding of the package, that expands rapidly on reflow. The effect is named because the failure can be heard as a sharp 'crack' if the component is heated using a rework station. Plastic BGAs are potentially more vulnerable to popcorn failures than QFP packages, because the organic substrate materials

(e.g. glass epoxy, polyimide or bismaleimide-triazine resins) used in BGAs have higher moisture absorption rates than the epoxy moulding compounds used in conventional systems.

Popcorn failures may be avoided by heating the components in a dry air/nitrogen atmosphere to drive off any absorbed moisture before reflow, or by designing packages which incorporate open thermal vias beneath the die [18]. These vias act as vents, through which water vapour can escape when the package is reflowed.

Voids in the solder joint

Voiding in BGA solder joints is a potential issue of reliability. The generation of voids could be caused by solidification shrinkage, moisture and flux volatilisation. The major cause is probably due to gaseous products resulting from flux volatilisation - trapping voids in the upper surface [19]. The actual effects of solder joint voiding on joint reliability is still not totally understood. However large voids (40% of the ball joint) or incidences of high voiding should be avoided. Solder joint voiding at levels equivalent to 24% of the pad area have been reported as causing no negative effect on the assembly reliability. Also solder joints with voids up to 16% showed improved reliability performance than those without voids [20].

Thermal Fatigue

Many reliability studies concentrate on the thermal fatigue of the solder ball joints but investigations into the effects of intermetallics at the solder-pad interface have also been conducted [21]. Thermal fatigue induced by differences in thermal expansion between board and package materials is probably the most common failure mode for ball grid array packages. Whilst similar strains are experienced in all electronic packages, the strain seen by

the solder is increased in ball grid array applications, as there are no compliant leads to absorb any of the strain induced by the thermal mismatch between package and board. Cracking of the solder joint, induced by thermal fatigue, has been identified as a major failure mode in electronics packages [22,23]. The thermal fatigue lifetimes of assembled BGA systems depend on the specific CTE mismatch between the substrate and the PCB, the stand-off height, the size of the package, and the type of solder used. Assuming that adequate process control has been implemented during assembly, BGA reliability is generally less sensitive to process variations than QFP. Thus, ball grid arrays provide a tighter fatigue life distribution than QFPs [24].

Thermal fatigue effects are greatest in ceramic packages on epoxy boards, as these systems have the largest material CTE mismatches. In this case, column grid arrays may be used to enhance the fatigue life by increasing the stand off distance. The effect is also found in plastic overmoulded packages due to the strain induced by the silicon die, and by different moulding compounds or metal heat spreaders [25]. In the case of BGAs constructed from thin laminates with the die bonded directly to the laminate, the greatest strains are found beneath the edges of the silicon die. In this case, fatigue life may be extended by depopulating the area immediately beneath the silicon die; i.e. by having solder balls around the perimeter of the package and at the centre only.

Conclusions

Ball Grid Array packages, and their derivatives, have the potential to enter the mainstream of electronic assembly.

The main area array formats have been identified as:

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- Plastic Ball Grid Arrays
- Ceramic Ball Grid Arrays
- Ceramic Column Grid Arrays
- Tape Ball Grid Arrays
- MicroBall Grid Arrays.

This paper has highlighted some of the potential problems that could result in poor performance of array package technology and how industry is overcoming these. Much of the assembly process uses technology already well established in the industry, however the absence of simple and low cost inspection systems requires tight control of all steps.

There are always going to be changes in electronic packaging technologies, the change from QFP to BGA is not the final step. However, the need for change is driven as a result of limitations that arise in the techniques currently being used. The lessons learnt from each technique are then built upon. The processes in which BGAs are assembled and inspected should be readily adaptable to the next generation devices, that will probably include chip scale packages along with other novel packaging techniques.

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