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The trouble with BGA solder joints

The increasing density of modern assemblies always imposes new requirements on the packaging technology of the used chips. Especially BGA housings are in the centre of attention. However, the terminals of those components escape from physical probing and visual inspection. This fact gives rise to the question, how to ensure the quality of those solder joints with extremely reduced access. The following article analyses the situation of using BGAs. It shows up problematic issues and discusses available system solutions and their application strategies in production practice.

All That Glisters is not Gold

The ever progressing employment of surface mount technology (SMT) has been further accelerated by the introduction of BGA housings in the mid 1980s. This package has all of the terminals as solder balls on its bottom side. Compared to wired ICs, BGA technology provides many advantages, like, e.g.

- smaller packages
- increased packaging density
- increased pin density
- improved signal transmission characteristics
- improved thermal linkage with the board

The latest packages of this type, e.g. VFBGA (very fine BGA) meanwhile permit several thousand pins and a pitch of less than 0.5 mm.
BGAs are assembled in an according soldering process with many influencing parameters. This process normally leads to a partly matt-finished solder joint, which has to meet various mechanical and electrical criteria:

- strong bonding between ball and board
- high mechanical long-term stability
- high structural integrity of the ball
- high conductivity
- high electrical signal integrity
- high insulation strength between neighbouring pins

Even at this early point of discussion, the interaction between physical conditions and the resulting electrical properties is quite obvious.
The reference model in figure 1 shows a simplified illustration of the structural relationships. A static, oriented signal with simple ohmic resistors is assumed. The chip's internal conditions (bonding wired etc.) are regarded o.k. and thus are neglected here.

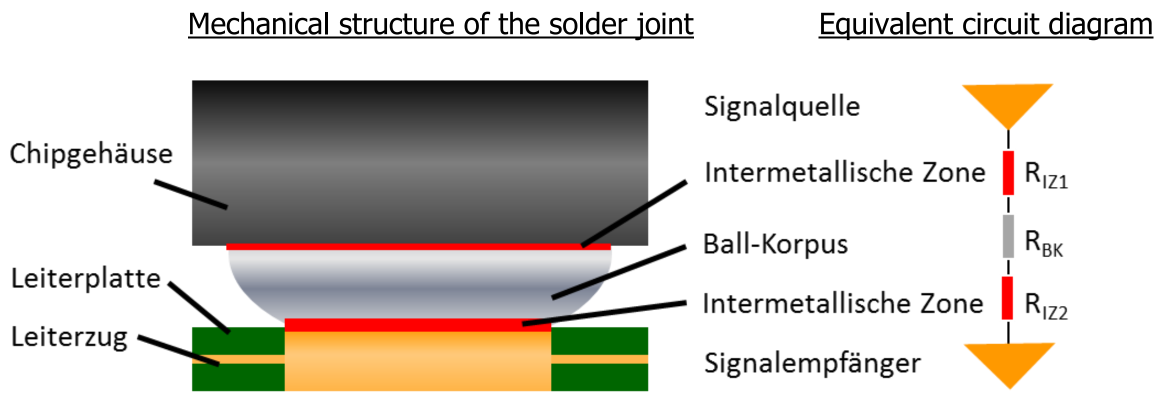

Figure 1: Static reference model illustrating corresponding mechanical and electrical design

During reflow, the solder of the balls and the solder paste will melt and through a chemical reaction an intermetallic zone will be formed between molten solder and board surface. Another intermetallic zone exists between ball and chip. It is build up during manufacture of the BGA chip and shall be checked by the BGA manufacturer. From the electrical point of view, the line resistance of the ball and the intermetallic zones is essential. Normally, the resistance between signal source and sink should remain stable in the milliohm range.
But all theory is grey and in practice systematic and random errors occur and lead to heavily altered parameter values. Even shiny solder joints are far from being a guarantee for solder joint integrity.

To Know What Holds the Universe Together in its Innermost Folds

Soldering defects arise from quality defects of the elements to be soldered, but also from deviating soldering profiles. The error patterns may differ widely. They range from visible deformations of the joint in the sense of insufficient or excess solder, where the electrical contact may be given, to visually perfect solder joints with random or even no contact.
With regard to evaluation of a BGA solder joint, the standard IPC-A-610E [1] plays an important role. It sets up acceptability requirements for electronic assemblies and identifies criteria for BGA components. In a production environment system solutions are necessary, which are capable of verifying compliance of the solder joints with that standard. This helps to avoid structurally unstable solder joints, which may break under mechanical load and loose electrical conductivity. It should be noted, however, that many defects, which are related to the form of the solder joint, will show electrical effects only under extreme conditions.
In contrast, failures in the intermetallic zone are particularly devilish and hard to recognise. "Head in pillow" and "black pad" are widely known phenomena of that kind. With the first effect, the solder doesn't fuse with the solder paste, so sort of barrier layer will be build up. The visual appearance of the solder joint, however, normally doesn't reveal that. This effect is mainly caused by contamination of the ball surface.
On the other side, the black pad phenomenon is more related to board issues. Here, the ball reacts with the solder paste, but below it, a layer is build up with reduced or entirely missing conductivity. This phenomenon is mainly caused by quality defects of the surface of the board's pads. Table 1 gives an overview over the fault categories discussed so far.

Fault category	Mechanical/visual appearance	Electrical appearance	Potential cause of failure

Faulty ball	- incorrect ball shape - incorrect area/size - voids - incorrect position - wrong ball pitch - poor coplanarity between chip and board	- R_{BK} hardly changed - $R_{BK}=\infty$ (open joint) - short circuit between balls	- BGA chip (ball) - solder paste quality - solder paste application - assembly offset - soldering profile - pad design
bonding weakness between ball and solder paste "head in pillow"	- correct ball shape - contamination layer between ball and solder paste - no mechanical strength	- $R_{IZ}=\infty$ (open joint) temporary contact due to mechanical loading	- BGA chip (ball) - solder paste quality - soldering profile
bonding weakness between solder joint and board "black pad"	- correct ball shape - contamination layer between ball and solder paste - cracks in the intermetallic zone - dark pad discolourations - low mechanical strength (tear off)	- $R_{IZ}=\infty$ (open joint) - temporary contact due to mechanical loading - R_{IZ} is in normal range, however connection tears off on loading (open joint)	- board quality - soldering profile

Table 1: Overview over typical fault categories of BGA solder joints

As the table shows, there is a number of fault scenarios, and all of them must be controlled to ensure the required production quality. What's more, in practice the typical problems vary between different manufacturers, and sometimes even between different products in the same production site. Possible faults in intermetallic zones with sporadic contact failure are an essential threat and may lead to catastrophic consequences for critical applications in e.g. automotive electronics. Depending on the respective situation, appropriate test equipment technologies should be used. But which technologies meet these requirements best and is there an ultimate strategy for quality assurance per se?

A Look Behind the System Scenes

The use of test and inspection systems basically has two key strategic objectives. On the one hand, all production process faults shall be found, and on the other hand, each system acts as a process sensor in the required control loop of quality assurance. In practice, there is a number of different technologies available to meet this challenge, however only a few are suitable for BGA solder joints. This is all the more true, if an IPC-A-610 compliant production has to be demonstrated. Modern 3D inspection systems are capable of quantitatively measure solder joints, whereas electrical test systems can only provide pass/fail information about the contact status. Table 2 lists the capabilities of various test/inspection methods with respect to essential test criteria and technical features. Methods include AOI (automated optical inspection), MXI (manual X-ray inspection), AXI (automated X-ray inspection), AXOI (automated X-ray/AOI inspection), Boundary Scan (IEEE1149.x), ICT (in-circuit test) and FPT (flying probe test).

Feature	AOI	MXI	AXI	AXOI	BScan	ICT	FPT
Qualification of the BGA chip (IPC-A-610E)	-	√*	√ [3D]	√ [3D]	-	-	-
Bonding weakness in intermetallic zones	-	√*	(√)	(√)	-	-	-

Co-planarity of the IC	√	-	(√)	√	-	-	-
Rotated IC	√	-	-	√	-	-	-
Conductivity of the solder joint	-	-	-	-	√	√	√
Defective el. driver/sensor	-	-	-	-	√	√	√
Access to traces via micro-miniature test points	-	-	-	-	√	-	√
No physical access to the trace	-	-	-	-	√	-	-
Adapterless operating principle	√	√	√	√	√	-	√
Full in-line speed	√*	-	√*	√*	√	√	-

√* system dependant (√) restricted by technology

Table 2: Performance of various technologies regarding identification of BGA faults

It quickly becomes evident, that there is no universal solution available. Each technology aims at certain defect classes. MXI systems offer high resolution in the lower micron range and thus are capable of detecting all mechanical defects. However, they are pure off-line machines and can't be used for automated operation. Quite the opposite is valid for AXI systems. They are in-line capable in principle and 3D machines can qualify according to IPC-A-610. Unfortunately, they have a lower resolution, so they have problems with detection of poor bonding in intermetallic zones. AXOI devices combine AXI and AOI into one system. So they are capable of putting down BGA solder joint defects to incorrectly placed chips.

In the field of electrical tests, physical contactability of traces plays an essential role for the applicability of those technologies. High-density BGA assemblies with completely embedded traces push long-term reliable test methods like ICT and FPT into an increasingly marginal role. The Boundary Scan test method is known as a ground-breaking alternative: it is standardised according to IEEE1149.x [2] and operates adapterless.

Based on the already discussed production test requirements, for complex BGA assemblies two technologies crystallise: X-ray systems (AXI and AXOI) and Boundary Scan systems for the electrical counterpart. Both methods will be discussed in more detail in the following. A complementary situation is assumed, because an electrical test yields no information on the mechanical status of the solder joint and an automated inspection of the solder joint doesn't guarantee an electrically perfect signal transmission.

Maxing Out the Potential of X-Ray

Even if in principle X-ray technology is capable of watching the balls by taking a look through the BGA, this is only a required technical prerequisite. The effective customer benefit is primarily defined through the technological device concept. In modern SMT production environments, X-ray systems are deployed in-line or as a stand-alone solution to perform fully automated X-ray inspection. Also the use of high-resolution manual or semi-automated X-ray devices (MXI) for sample analysis is widespread.
In sum, AXI systems for use with BGA assemblies in SMT production lines must meet some basic criteria, like e.g.

- Full inspection according to IPC-A-610E
- Low fault slip
- Low false alarm rate
- Throughput matching the beat rate of the production line (in-line operation)
- Automated fault detection
- Simple programme generation
- Intuitive user interface
- Support of statistical process control (SPC)

Regarding BGA components, IPC-A-610E deals with criteria like solder ball offset, solder ball distance, solder ball form and voids in the solder joint. It is also associated with IPC-7095B [3], which specially deals with design and process development of BGAs. To check assemblies according to the requirements of IPC-A-610, tomosynthesis-based 3D AXI systems, like e.g. OptiCon X-Line 3D from GOEPEL electronic [4], are particularly effective.

Figure 2: OptiCon X-Line 3D with integrated AOI option (AXOI)

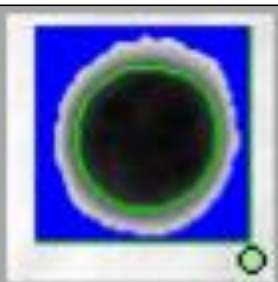	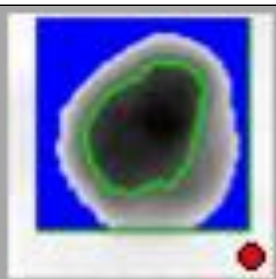	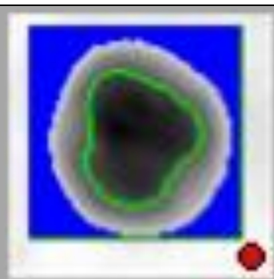
Well soldered BGA ball, roundness OK area OK grey level OK	**Poorly soldered BGA ball, roundness NOK area NOK grey level OK**	

Figure 3: Measurement of good and poor solder joints

The examples in figure 3 show a solder ball and its vision evaluation. The images illustrate a cut through the centre level of the BGA balls.
The evaluation yields results like ball area, roundness of the ball, position of the ball and its grey level. Here, the X-ray technology demonstrates its strength, delivering real measurement values. X-ray images show changes in the material itself, as well as changes in material density and thickness.
Voids are just an additional criterion of BGA ball integrity. They arise, amongst other things, during the reflow process, when the flux of the solder paste is heated up and transferred into a gaseous state and gets entrapped by the solder of the ball. Voids may also originate from the board design, when e.g. pads feature microvias. Size and number of voids depend mainly from the selected solder paste, the flux percentage and the chosen temperature curve of the reflow oven. The following example shows, that also the amount of printed paste influences void generation.

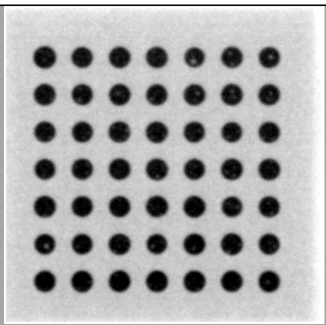	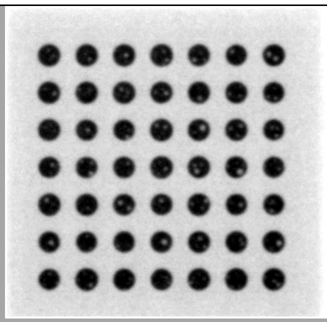	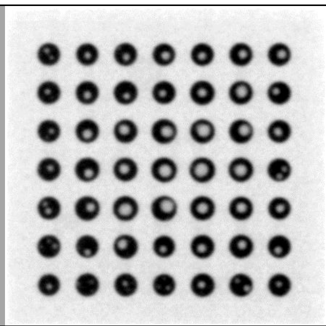
BGA – 50 percent solder volume, low voiding	**BGA – 100 percent solder volume, low voiding, slightly increased ball area**	**BGA – 200 percent solder volume, strong voiding visible**

Figure 4: Illustration of voids

Typically, during void checking, the void area (not the void volume) is determined. Mainly, the ratio between void area and ball area is calculated and given as a percentage. Assuming that voids take a spherical shape, the void volume can be calculated from the void area. In practice, however, this is rather atypical. The OptiCon X-Line 3D system determines the void area in the centre level of the BGA balls. The image down left illustrates automatic void determination. IPC-A-610E sets the limit value for voiding at 25 percent of the total solder joint area.

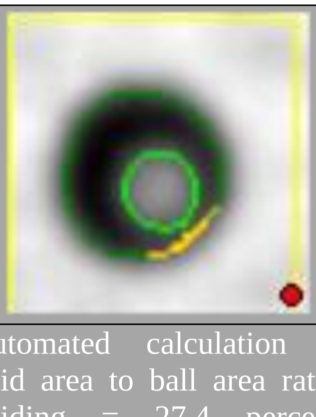	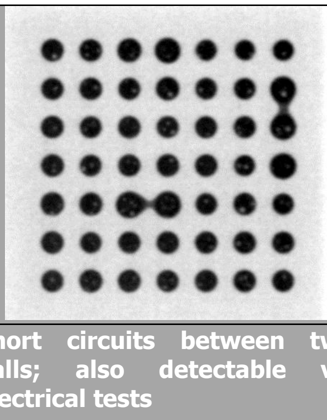	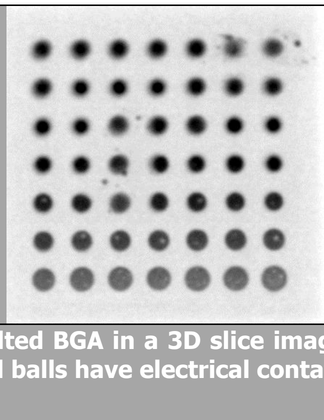
Automated calculation of void area to ball area ratio; voiding = 27,4 percent; measuring plane = ball centre	**Short circuits between two balls; also detectable via electrical tests**	**Tilted BGA in a 3D slice image; all balls have electrical contact**

Figure 5: Illustration of voids, short circuits and non co-planar BGA device
According to figure 5, solder balls can not only be evaluated with regard to shape, presence and voids. Even short circuits between solder balls can be detected.

Figure 5 also shows a tilted BGA. All balls have electrical contact and received a "pass" from the Boundary Scan test. The optical evaluation, however, unveils the tilting in the 3D X-ray image (slice plane = ball centre of the bottom row). This BGA will probably fail, if it will be mechanically or thermally loaded. Such tilting may be caused by wandering components that settled under the BGA.
The fault scenario of the "head in pillow" effects has already been discussed. One approach to evaluate this fault scenario in a safe and reproducible way would be to use the tear drop pad design. Here, terminal pads of the BGA are not round, but rather tear drop shaped. Figure 6 illustrates that in an X-ray image.

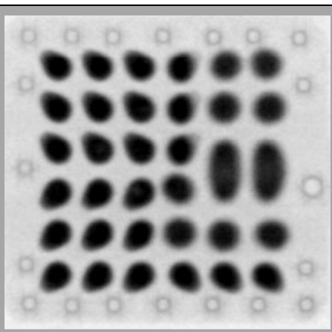	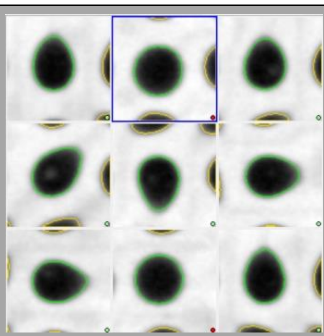
X-ray image of a BGA with tear drop pad design; round solder shapes indicate a ball "resting" on a pad	**Section from automated evaluation of BGA balls from figure 6. Balls from top and bottom position of the middle row are faulty and "rest" on the pad**

Figure 6: "Resting" balls (head in pillow) visible due to tear drop pad design

When a ball melts and fuses with the underlying solder paste, the typical tear drop shape will be visible. If the ball doesn't fuse with the solder paste, it will keep its circular shape and can be identified by parameters like roundness, axis ratio or ball area.
The tear drop design often cannot be used with smaller pitches. The tear shape decreases the distance between two pads and the minimal insulation clearances may be violated.
Then the classical round pad layout must be chosen, which has to be considered when parameterising the X-ray test.
A sole evaluation of the solder joint according to its ball form is often insufficient for distinguishing between good and bad. In the case of single-sided assemblies, the transition between pad and solder ball can be evaluated using a high resolution 2.5D X-ray system. A visible necking-down would indicate a "resting" ball: the head in pillow situation. If, however the assembly is populated on both sides or has even more than two soldering planes, this approach is somewhat problematic. The 2.5D X-ray image then shows strong superimpositions of the BGA with components from the other side. Figure 7 shows a board section with three soldering planes (TOP = capacitors, BOTTOM 1 = BGA_1, BOTTOM 2 = BGA_2).
Here, only a 3D X-ray system will provide a remedy. The OptiCon X-Line 3D system uses tomosynthesis to get one layer of the board into focus. This approach enables users to check solder joints without overlapping effects.

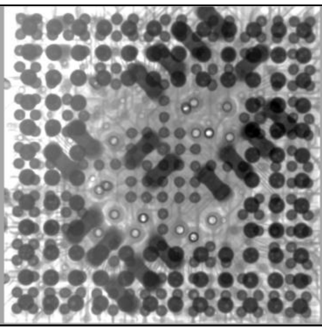	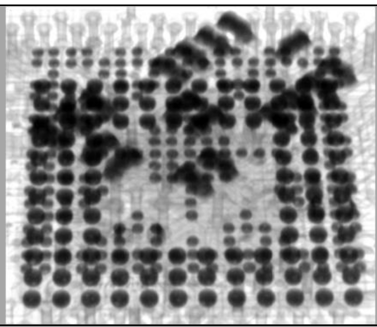	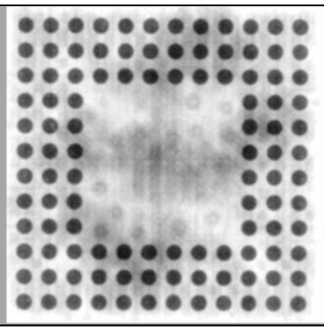
Vertical view (2D) using GOEPEL's semi-automatic X-ray system ScopeLine MX; superimposition of three assembly layers recognisable	**Angled view (2.5D) using GOEPEL's semi-automatic X-ray system ScopeLine MX; superimposition of three assembly layers recognisable, first bottom row of balls evaluable**	**3D slice image of the middle layer using GOEPEL's OptiCon X-Line 3D. All rows of balls evaluable**

Figure 7: Different radiographic views using 2D, 2.5D and 3D technologies

ScopeLine MX [5], a semi-automated X-ray system for off-line analysis is available from GOEPEL electronic's product portfolio.

Figure 8: ScopeLine MX-1000 for semi-automated BGA analyses (MXI)

It Does Better Without Nails

As addition to X-ray inspection of complex BGA assemblies, Boundary Scan is the method of first choice. As opposed to classic in-circuit test physical nails are "moved" into the chips and become virtual nails (see fig. 9).

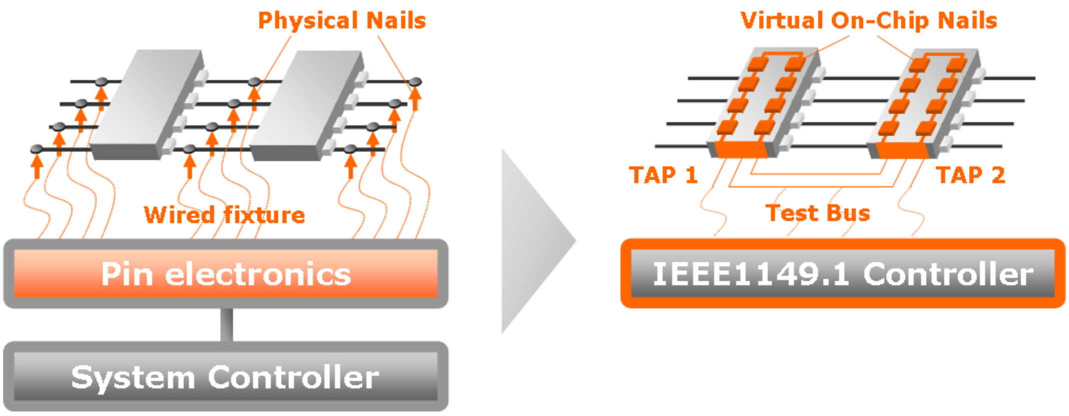

Figure 9: Transition to design-integrated test electronics

This design-integrated test electronics is serially controlled via a test bus. The virtual nails are in fact Boundary Scan scan cells, arranged as a shift register (Boundary Scan register). The synchronous handling of the cells makes the electrical test of BGA solder joints a simple task. However, in the case of directed connections (fig. 10), the failure location can't be exactly nailed down. For that, an MXI-like method would be required.

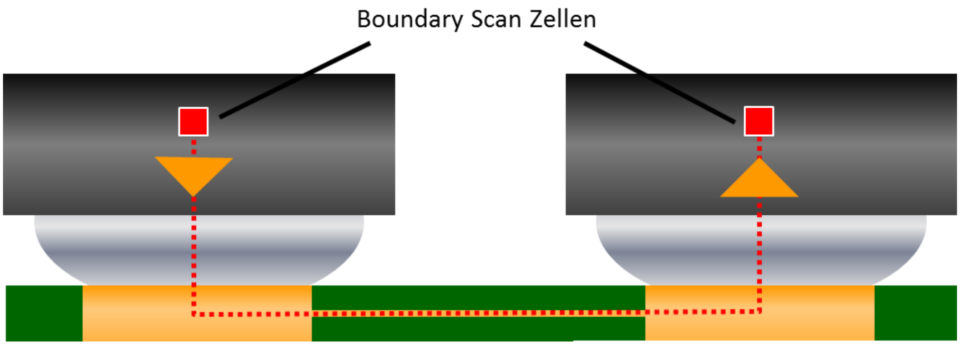

Figure 10: Connection test of two BGA pins per Boundary Scan

Multi-point connections, like e.g. bus structures, provide pin-level fault diagnostics. What's special about Boundary Scan is its high testing speed and its flexibility when it comes to prototype tests. Sophisticated system solutions like the software platform SYSTEM CASCON™ [6] from GOEPEL electronic feature automated test pattern generators (ATPG), which are capable of testing thousands of solder joints in parallel within a couple of seconds, including automated pin fault diagnosis without requiring any test fixture. This cost efficiency can hardly be topped.

Boundary Scan is a structural procedure and, as such, independent from the chip's integrated functional logic. Finally, that means, that each pin can be tested independently. So, this procedure can be ideally combined with stress testing, where e.g. thermal cycling in a climatic chamber tries to force bad solder joints to fail. For this kind of application GOEPEL electronic provides pre-configured hardware modules like TIC03 from the SCANFLEX series [7].

But Boundary Scan also has its strengths in lab use. For rapid prototype verification designers often need to evaluate certain signals. For that purpose, graphical tools like Scan Vision™ yield best results.

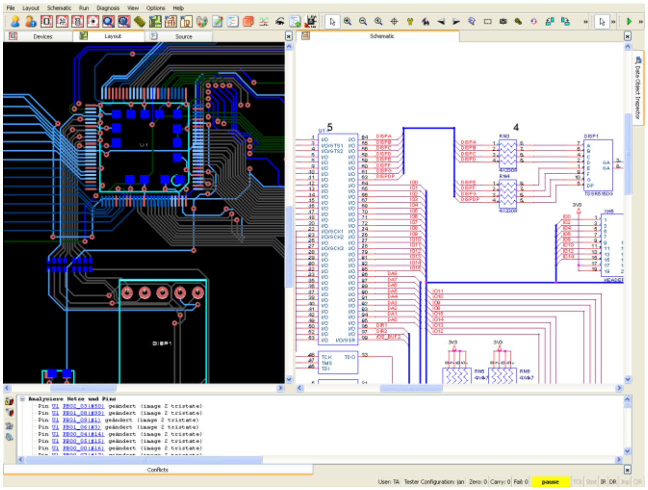

Figure 11: Representation of layout and schematics while running interactive pin toggling

It not only features cross referencing between layout and schematics. Boundary Scan cells can be activated by simply clicking on the respective pin. The resulting logic signal states are displayed using customer specific colour schemes.

For the first steps with Boundary Scan, special packages like the PicoTAP Designer Studio [8] are available from GOEPEL electronic. They feature all necessary tools including ATPG and debugger as well as the required hardware to be used immediately. A hardware module to test I/O signals is also included. Among the particular attractions of these packages is their extremely favourable price/performance ratio.

Figure 12: Components of the complete package PicoTAP Designer Studio

Powerful in a Process Team

The very existence of the discussed technologies and system solutions isn't sufficient for a production with highest quality standards. The use of X-ray systems and Boundary Scan systems in the production of BGA assemblies requires a thorough analysis of the entire production situation. Accurate knowledge of the expected faults and their statistical distribution is of paramount importance. There are more than 100 parameters, which influence the definition of an optimised inspection and test strategy. So it is impossible, to name here the "ultimate" strategy. But one thing is certain: the combination of AXOI and Boundary Scan for BGA assemblies is capable of delivering a fault coverage close to 100 percent. And the higher the percentage of BGAs, the higher the importance of these technologies. In today's situation, they seem to be the only solution for HDI assemblies. Figure 13 illustrates a possible production line for that situation.

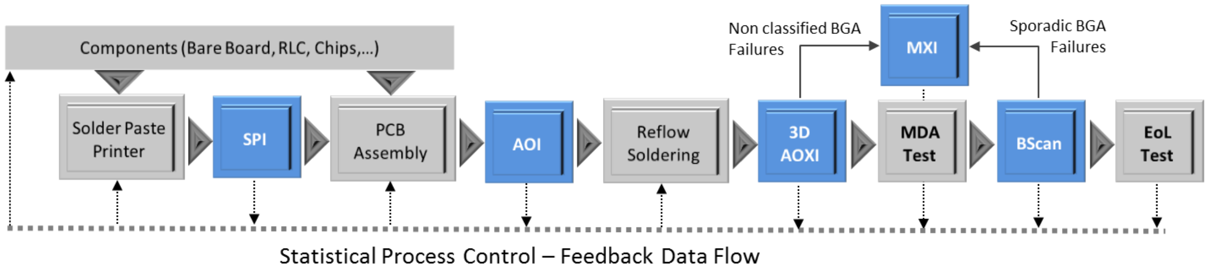

Figure 13: Example of the use of AXOI, MXI and Boundary Scan in a BGA assembly line

The basic idea is, to install a sensor after each production process and to feed back statistical fault information to all process steps. Due to its high inspection speed, the AXOI system can qualify the assembly according to IPC-A-610E and measure, for example, the inner solder meniscus of TQFP components. The still missing mechanical fault coverage will be ensured by the integrated AOI system. The MXI machine is used for high precision analyses. All sensors, which are illustrated in blue, are included in GOEPEL electronic's product portfolio.

Summary and Conclusions

BGA components are an important part of complex board assemblies. They permit ever higher densities and improvements of electrical parameters. The steadily decreasing node access enforces appropriate countermeasures to be taken in the form of alternate inspection and test methods. In practice, particularly 3D AXOI machines (combined AXI/AOI systems) plus electrical Boundary Scan test methods have the greatest potential to solve those access issues. Both methods complement each other perfectly and permit a fault coverage for BGA solder joints of almost 100 percent. Furthermore, Boundary Scan has a fundamental future proofness, as it is based on progressive IEEE standardisation activities [9], [10]. GOEPEL electronic developed the concept of Embedded System Access (ESA) that uses these standards and supplements them with additional technologies to extend fault coverage [11]. And this makes that combination even more attractive.

First of all, the optimal use of the discussed system solutions requirea a thorough analysis of the entire process situation.

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