DFM Rules for Smartphones: An Analysis of Yield on Extremely Dense Assemblies

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Abstract
Handheld portable products such as smartphones are trending toward smaller form factors while simultaneously increasing in functionality to keep up with consumer demands. This is achieved in part by decreasing the size of components and increasing the density of the circuitry. These unique product needs drive different Design for Manufacturing (DFM) recommendations than those that are in use for larger products – while for larger products, reworkability is paramount, for handheld portable products, high first pass yields and fitting the required functionality into an appropriate form factor are of greater concern in many cases.

This paper summarizes a new test vehicle designed to emulate a next-generation smartphone product. One of the goals of this project was to study the effect of pad design and component spacing on assembly yield. The test vehicle includes a representative range of component types including 01005 and 0201 discretes, 0.3mm pitch CSPs, Package-On-Package, QFNs, and RF shields. For selected components, different pad designs were included on the board, allowing a direct comparison of the various options and recommendations for the optimal pad designs. In addition, a range of component to component spacings were used on the board, ranging from spacings in common use in today's products to extremely aggressive spacings that push the limits of the PCB manufacturers. The test vehicles were inspected after assembly, and yields were determined for the various component to component spacings studied to determine what the limitations are and to update DFM rules specific to the needs of extremely dense handheld portable products.

The results of the yield study will be presented along with the analysis of the implications for the DFM rules.

Introduction
It has long been considered good practice in the electronics industry to conduct a "Design for Manufacturability" (DFM) analysis of a new printed circuit assembly prior to releasing it to manufacturing. Ideally, DFM guidelines are used in the design of a product to ensure that few if any changes are required as a result of the review process. Companies base their DFM guidelines on years of experience in manufacturing various products, and these guidelines are critical in manufacturing high yielding products. DFM guidelines tend to be widely applicable to many types of product, but with the emergence of extremely dense handheld products such as smartphones, some limitations have become apparent in traditional DFM guidelines. In order to pack a maximum amount of functionality into an extremely small form factor, smartphone designers routinely have to break the types of spacing guidelines typical of most other electronic products. While there is a sound basis for the guidelines that have been established historically, they simply do not accommodate the needs of very dense assemblies. Many of the existing DFM guidelines are established with a view to enabling a cost effective, high yielding rework process for each component on the board, should it be necessary. The needs of hot air rework equipment are typically the limiting factor when defining DFM guidelines primarily due to features such as component to component spacings.

This paper describes the results from a project designed in part to re-visit design for manufacturability guidelines with the needs of handheld portable products, particularly smartphones, in mind. This project focused on determining which pad designs gave the highest possible first pass assembly yield for the type of extremely miniaturized components that are in use or will soon be in use on smartphone type products, such as 01005 discretes and 0.3mm pitch CSPs. The minimum spacing between different component types was also studied with a view to extending existing DFM guidelines down to absolute minimum levels. Primary attach assembly yield was the main criteria used to determine acceptable limits – most handheld portable products are manufactured in very high volumes, so first pass yield is critical. For some products, rework may be carried out if the value of the assembly makes it worthwhile, while for other products, rework is not economically feasible, and defective assemblies are discarded. While the focus of the study is primarily on first pass assembly yield, the intent is to study rework as well to determine whether further limitations on factors such as component spacing are required if a viable rework process is necessary.

Prior studies have been conducted in some of the areas of focus for this project. Considerable work has been done to determine the ideal pad dimensions for 01005 discretes and in developing a viable screening process for these extremely small components. Much of this development work to date has been performed on test vehicles that have only 01005 discrete components on them or where analysis has been focused purely on 01005 components on a test vehicle that is not specifically tailored to the needs of handheld portable products.[1,2]

Work has also been done in the area of broadband printing – that is, printing for assemblies with a wide range of feature sizes.[3,4] This study builds upon previous work by using a test vehicle with a wide range of components of a similar mix, level of assembly complexity and dimensions as what would be found in an actual smartphone product, and by including both screening studies and assembly yield studies.

Test Vehicle Description

Layout

The Smartphone Test Vehicle (SPTV) was designed to simulate a real smartphone product, and features a blend of next generation technologies and aggressive design features to push the limits of manufacturability. A wide range of components were selected to be representative of the mix of components that would be found on a typical smartphone assembly. The dimensions and stackup were also selected to emulate some types of smartphone PCB. Each assembly is a panel composed of four single-sided boards, as shown in Figure 1. The overall dimensions of the panel are 4.582" x 9.281", with a thickness of 0.040". The surface finish was OSP.

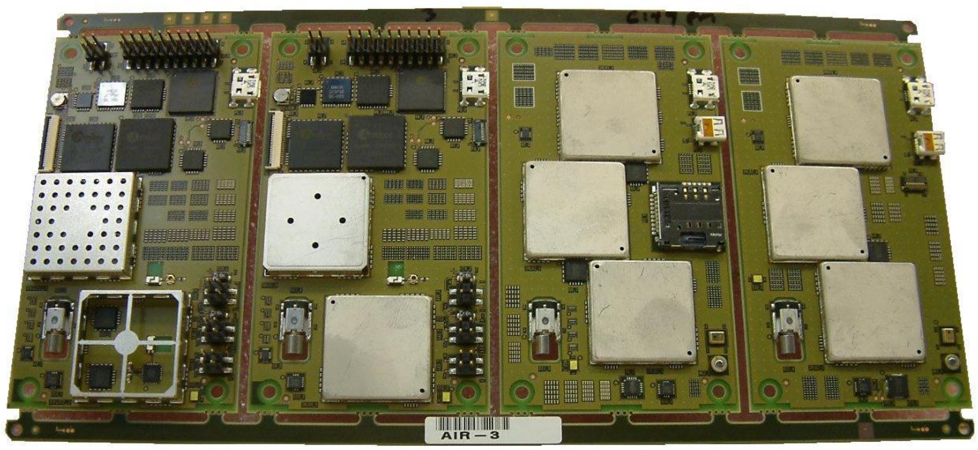


Figure 1 - Smartphone Test Vehicle (SPTV)

The test vehicle is designed to support two types of studies – Boards 1 and 2 on the panel contain features intended to facilitate reliability testing, including daisy chained components and connectors to allow easy connectivity to in-situ monitoring equipment. These boards also include RF circuits designed to test the effectiveness of different shield designs before and after reliability testing. The second key study area is manufacturing yield and DFM feature assessment. All four boards contain features that are part of the yield and DFM feature study, and this will be the primary focus area for this paper.

Components

The SPTV bill of material (BOM) contains nearly 50 different types of components, with a total of 3,770 placements per panel. While the components included many different types of devices, including motors, connectors and QFNs, this paper will concentrate on DFM results for 01005 and 0201 discretes, 0.3mm pitch and the spacing between discretes, CSPs and RF Shields.

Details of Design for Manufacturability Features

There are several DFM features included in the test vehicle, including pad design for selected components, discrete to discrete spacing, discrete to shield spacing, discrete to CSP spacing, CSP to shield spacing, CSP to CSP spacing, and shield to shield spacing. To select the dimensions to be included in the spacing studies, two factors were considered – what is currently in use, and what limitations are imposed by PCB fabricator design rules. Teardowns were used to determine what spacings are currently in use, and these values were used to define the high range of values to be studied. PCB suppliers currently producing smartphone PCBs in high volume were identified, and their capability matrices were used to determine the minimum values for the various parameters to be studied. For the pad design experiments, experience from previous experiments, information from teardowns and the PCB suppliers' capability matrices were used to define the variables to be studied.

For 01005 discretes, previous experimentation had defined a preferred pad size which was used for all 01005 locations on the SPTV test vehicle. The pad variations focused on the use of different shapes (rectangular or elliptical) and pad definition method (SMD or NSMD). The matrix of designs used is shown in Table 1.

Table 1 - 01005 Discrete Pad Design Variations

Shape	Solder Mask
Rectangular	Non Solder Mask Defined
Elliptical	Non Solder Mask Defined
Rectangular	Solder Mask Defined
Elliptical	Solder Mask Defined
Rectangular	SMD on one side, NSMD on the other

Pad design variations for the 0.3mm CSPs were also studied. The different variations are summarized in Table 2 for 0.3mm pitch CSPs.

Table 2 - 0.3mm Pitch CSP Pad Design Variations

Pad Dimensions	Solder Mask
Small	Non Solder Mask Defined
Large	Non Solder Mask Defined
Small	Solder Mask Defined
Large	Solder Mask Defined

A major portion of the DFM study was devoted to determining what the minimum acceptable spacing between adjacent components should be. To study the spacings between discrete components, 0201 capacitors were used. The spacing variations studied are summarized in Table 3. Spacing "A" represents the smallest distance between devices whereas Spacing "D" represents the largest. In all cases, the pad dimensions were held constant.

Table 3 - Discrete to Discrete Spacing Variations

Pad Definition	Spacing Between Devices
Solder Mask Defined	A (Smallest)
Solder Mask Defined	B
Solder Mask Defined	C
Solder Mask Defined	D (Largest)
Non Solder Mask Defined	B
Non Solder Mask Defined	C
Non Solder Mask Defined	D

The spacing between RF shields and discretes was the second factor selected for study. 0201 capacitors were used in this study as well, and had the same pad dimensions as in the discrete to discrete spacing study. The variations studied are summarized in Table 4. Spacing "B" represents the smallest distance between devices and Spacing "D" represents the largest.

Table 4 - Discrete to Shield Spacing Variations

Solder Mask	Spacing Between Devices
Non Solder Mask Defined	B
Non Solder Mask Defined	C
Non Solder Mask Defined	D
Solder Mask Defined	B
Solder Mask Defined	C
Solder Mask Defined	D

The spacing between discretes and CSPs was also studied – as before, 0201 capacitors were used for the discretes, and a variety of CSPs were used in the study. The spacing variations for the discrete to CSP study were the same as those used in the discrete to shield study and are shown in Table 4. The same spacing matrix was used in a study of the spacing between CSPs and RF shields – in this study, a 97 I/O 0.4mm pitch CSP was used along with a single piece RF shield.

The final two spacing studies focused on the spacing between adjacent CSPs and the spacing between RF shields. For the CSP to CSP study, a 97 I/O 0.4mm pitch CSP and an 84 I/O 0.5mm pitch CSP were used. Three different spacings were studied, with 4 mils between each of the levels. For the shield to shield spacing experiment, the spacing between two identical shields was studied. Four different spacings were studied – the highest three spacings were separated by 4 mils, and the fourth spacing was set at 0 mils – the two shields shared one pad wide enough to accommodate both shields.

Build Summary

The Smartphone Test Vehicle boards were built with a conventional SMT line process using Type 4 halogen-free SAC305 no-clean solder paste. The boards were screened with a 100µm (4mil) thick laser cut stencil. The stencil was electro-polished and coated to facilitate paste release. The stencil supplier had previously demonstrated capability for high quality 01005 printing. For these small stencil apertures, many factors in the stencil manufacturing process become critical in order to obtain consistent paste release. For the TMV PoP component, the top package was dipped in no-clean PoP flux in a linear dip fluxer.

After the stencil printing process, the screened boards were sent through the automated paste inspection (API) equipment to measure and record the solder volume deposits present on the circuit board. Due to the smaller paste deposits, it was necessary to switch the standard sensor on the machine with a high resolution sensor. Gage R&R studies were performed and small changes were made to the program for optimization.

After the placement process, 100 panels were sent through a 10 zone reflow oven in air environment while 50 panels were sent through a nitrogen reflow environment at approximately 300 ppm of O_2. The reflow peak temperatures ranged between 235^{o}C and 240^{o}C, with a time above liquidous (217^{o}C) ranging from 53 to 61 seconds.

All reflowed boards were sent through automated optical inspection (AOI) and automated x-ray inspection (AXI). The AOI supplier helped develop the 01005 inspection algorithms and ensured optimal equipment performance. The defects found by the equipment were recorded and validated. To validate the automated inspection, manual visual inspection was performed on all boards to ensure data integrity. Table 5 details the build plan variations used in this evaluation.

Table 5 - Build Plan Variations

Component Population	Build Qty	Reflow Environment
Boards fully populated	50	Air
Boards with unpopulated components	50	Air
Boards with unpopulated components	50	Nitrogen

Results

Paste Inspection Results

The following histograms show the solder paste volume for the smaller discrete components and smaller CSP components on the SPTV. There was a general trend for smaller NSMD pads to have more solder paste defects and variation. SMD pads have tighter volume distributions as stencil aperture size decreases.

In Figure 2, the Elliptical NSMD pads performed poorly with many insufficient solder defects. Rectangular NSMD also had many issues with insufficients. The SMD pads performed the best, particularly the Elliptical SMD pads which had the smallest standard deviation for solder paste volume. The 01005 stencil apertures were 1:1 to the pad.

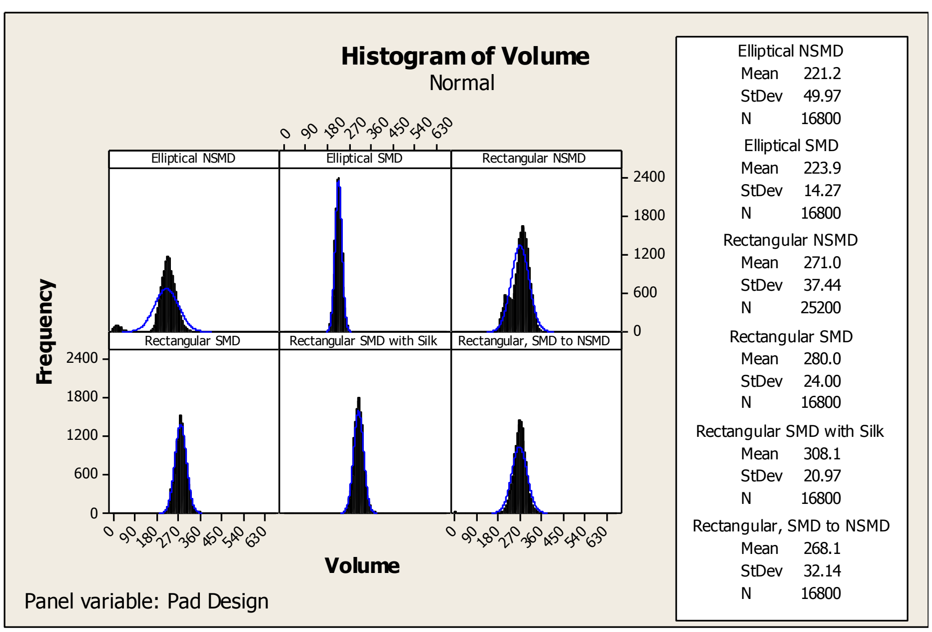


Figure 2 - 01005 Paste Volume Distribution by Pad Design

In Figure 3, solder paste volume for 0201s was within the desired limits and no issues were seen with these prints. The 0201 stencil apertures had a slight reduction from the pad geometry.

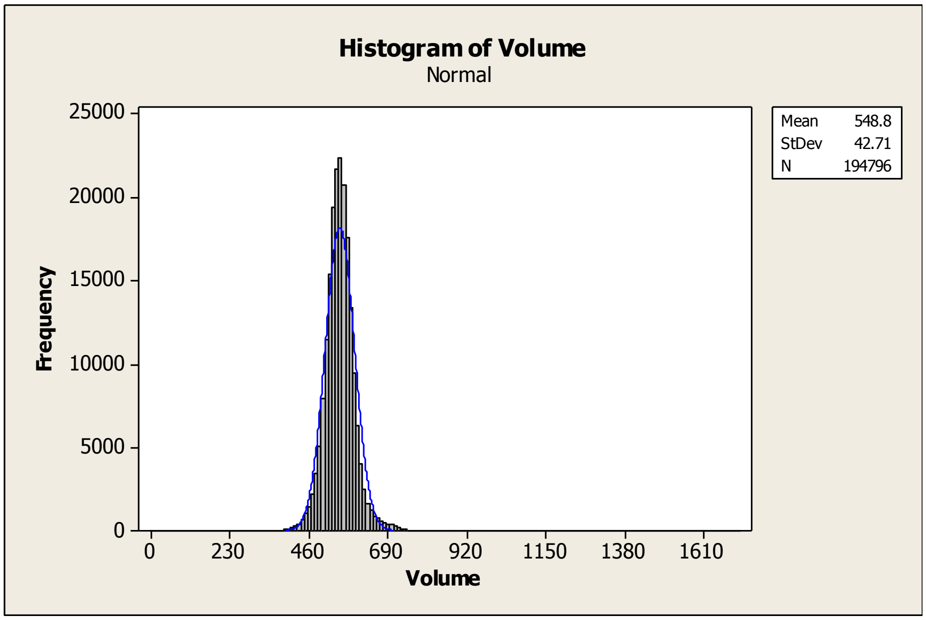


Figure 3 - 0201 Paste Volume Distribution

In Figure 4, for the 0.3mm CSP prints, the NSMD small pads printed the worst with the highest standard deviations for solder paste volume. Overall, there was too much solder paste being printed, which resulted in high levels of bridging defects. The stencil apertures were the large size for both small and large pads.

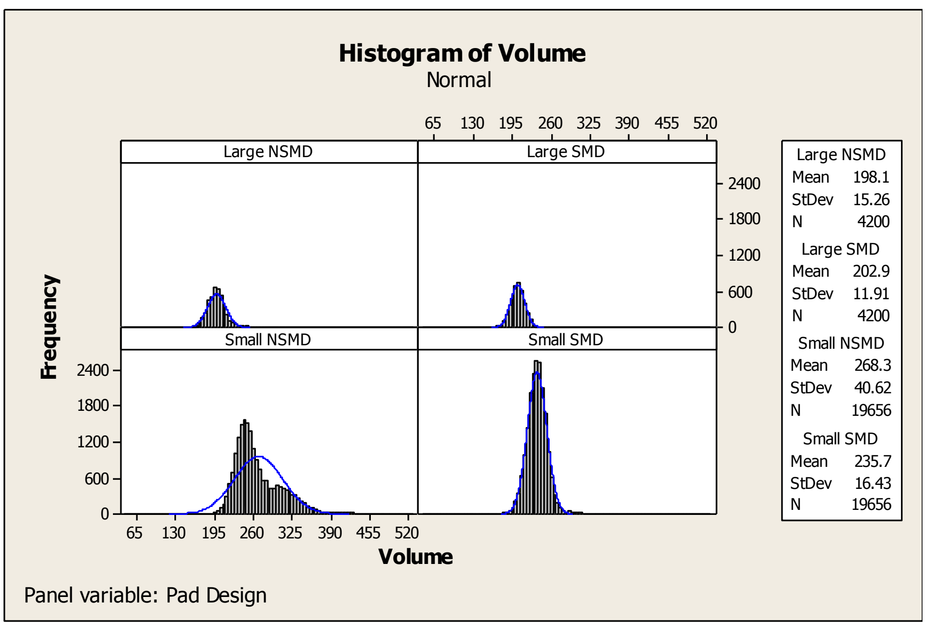


Figure 4 - 0.3mm CSP Paste Volume Distribution by Pad Design

Assembly Yield Results

The assembly yield of the 150-panel build is shown below in Table 6 sorted by component type. The defects included in this analysis take into account both the standard features and the 'design for manufacturing' features included in the board design. There were solder balls observed on the majority of panels, however, there were none which were large enough to be considered an IPC-610E[5] defect. The highest resulting defect was the 0.3mm CSP components, with 173 / 600 defects observed, followed by the 0201 components with 142 / 348,000 defects. The defects for each component are discussed further in the following sections.

Table 6 - Assembly Yield Results

Part Type	Visual Defects	X-Ray Defects	Opportunities	PPM
0.3mm CSP	1	172	600	288,333
0201	142	0	348,000	408
01005	6	0	195,000	31

Solder Balls

To gather data on the solder balls, 3 panels assembled in air were randomly selected and each solder ball present was counted, regardless of size. From this analysis, there was an average of 944 solder balls per panel, each of which was located near the 01005 and 0201 discrete components. When analyzed further, it was noticed that 91% of the solder balls were in and around discrete components assembled on solder mask defined (SMD) pads and 9% located near non-solder mask defined (NSMD) pads. The occurrence of solder balls near SMD pads seem logical, as when screen printing onto an SMD pad, it is more likely that solder paste will be printed onto mask, and during reflow this will break away and form a solder ball. Historically, the presence of such solder balls would result mainly in a cosmetic concern, however now with the presence of the very small 01005 components, the formation of a solder ball in the wrong position of the board, such as the one shown in Figure 5, could result in an electrical failure.

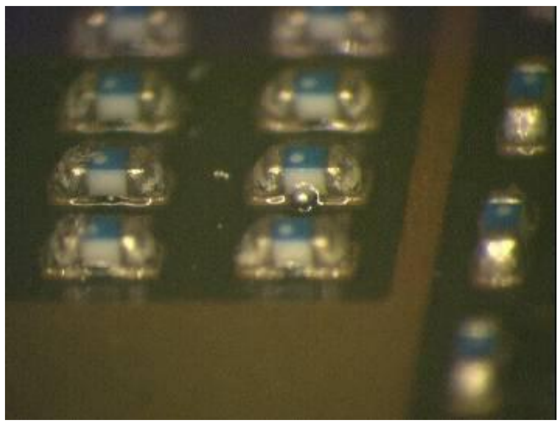


Figure 5 - Solder Ball on 01005 Inductor

01005 Discretes

Fixed pad sizes were used on this test vehicle based on previous 01005 test vehicle work, with varying geometry (elliptical vs. rectangular) and mask (NSMD vs. SMD). It had been determined, that with a 4mil thick stencil, smaller pad sizes than that would yield some level of paste defects as shown in Figure 6. The SPTV pad size (coded "F" in Figure 6 below) has an Area Aspect Ratio of 0.53 (traditionally, the target ratio should be >0.66). With a high quality stencil, this ratio could be printed with high repeatability without insufficient defects. A 3mil stencil would have been a better choice for 01005s, but to accommodate the larger paste requirements for some components, such as EMI shields, a 4mil stencil was used as the worst case scenario.

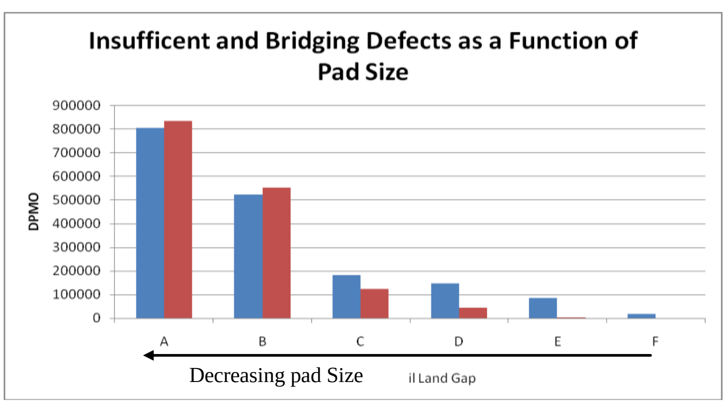
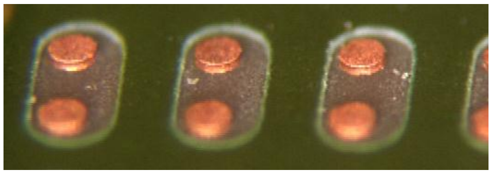
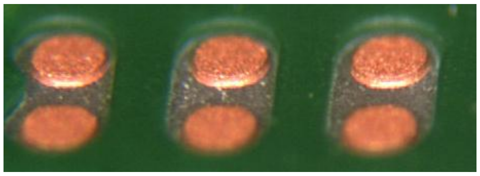


Figure 6 - Graph of Defects with respect to Pad Size

Incoming boards from 2 different suppliers were inspected and measured. From Supplier A, the 01005 copper pads were all over-etched, by as much as 2mils. Supplier B by comparison, was slightly larger (0.5mils) than the designed pad. Figure 7 shows the difference in pad size between Supplier A and B.

Supplier A **Supplier B**

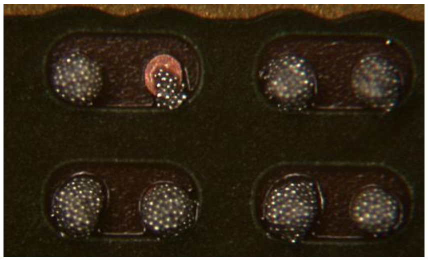
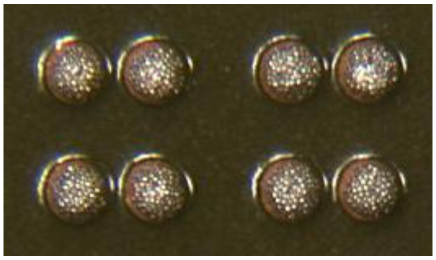
Figure 7 - Pad Size Comparison between Supplier A and B

When the build was completed by using Supplier A boards, the paste results are shown in Table 7. The NSMD pads performed worst, with many pads under the desired lower specification limit.

Table 7- Pad Solder Paste Volume and Defects

Pad Type	Total Pads	<Lower Limit	>Upper Limit	PPM
Rectangular, SMD	16800	7	0	417
Rectangular, NSMD	25200	45	2	1,865
Elliptical, SMD	16800	0	0	0
Elliptical, NSMD	16800	686	0	40,833

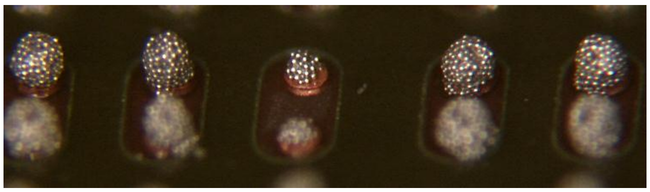
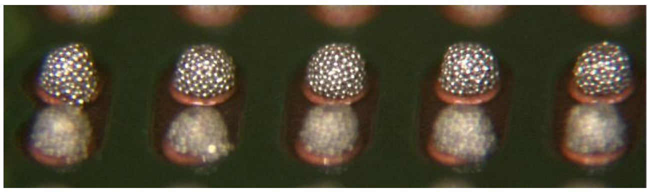
From previous test vehicle experiments, an Elliptical NSMD pad should have performed much better as shown in Figure 8a where the paste deposits are inconsistent. It was suspected that the over-etching of copper affected the area aspect ratio for printing. By calculating the area ratio of the (reduced) copper pad with respect to the wall area of the stencil aperture, the effective ratio changes from 0.53 to 0.33.

a) Elliptical NSMD Pads b) **Elliptical SMD Pads**

Figure 8 - Elliptical NSMD Pads and SMD Pads

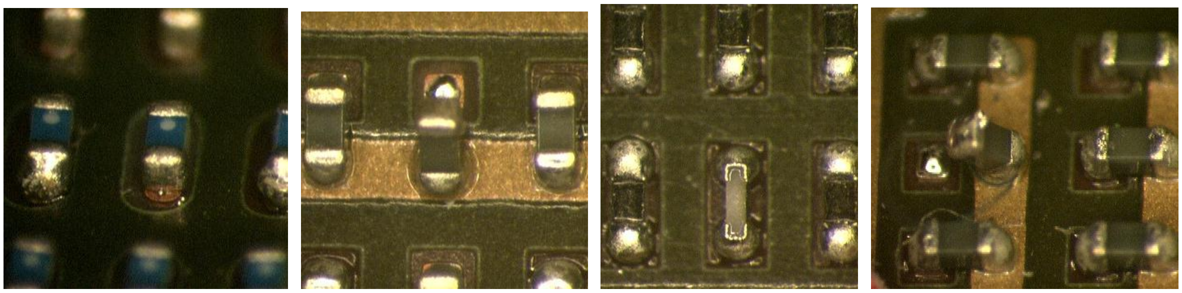
With SMD pads, the results were much better, particularly for the elliptical aperture as shown in Figure 8b where the paste deposits are more consistent. SMD pads have historically printed better for 01005s, because the size of the pad as defined by the mask, does not affect the area ratio like the copper defined pads. Paste tends not to stick to the FR4 around a copper pad, if the pad is on the small side. However, if the SMD window is small, the paste will more likely stick to the solder mask. Therefore, SMD pads are more forgiving to the screen printing process. Similarly, elliptical apertures have given more repeatable results than rectangular apertures for this test vehicle and previous 01005 test vehicles. The downside to SMD pads is that the board vendor may have a harder time controlling the registration of the mask, and when overprinting onto mask, solder balls are likely to appear as shown in Figure 5. Supplier B boards were screened and measured for comparison, and the results confirmed that with proper copper sizing, the paste deposits were more consistent. Figure 9 shows that Supplier B solder paste deposits were more consistent than the deposits found on Supplier A panels. Since the pad geometry is so critical to the 01005 process, it will be required to specify the acceptable tolerance to the bare board supplier.

Supplier A (over-etched copper) **Supplier B (correct copper size)**

Figure 9 - 01005 Solder Paste Deposit Comparison between PCB Supplier A and B

Of the (195,000) 01005s placed on the SPTV, there were 6 solder defects, not counting the insufficient paste defects caught at API as shown in Figure 10a . In summary, there were 1 missing component, 1 billboarded component (Figure 10c), and 4 tombstoned (Figure 10b). The tombstoned components were in the locations where the 01005 had one pad as SMD and the other as NSMD. It is unlikely to use this combination in a real design. It should also be noted that dust control is essential for 01005s. Dust can affect the solder paste deposit onto an 01005, and is even more likely to affect the placement of an 01005 onto the paste as shown in Figure 10d. For the SPTV build, even though the conveyors were covered, one defect related to a dust fiber was observed.



a) Insufficient Paste b) Tombstone c) Billboard d) Dust Fiber

Figure 10 - 01005 Defects found on SPTV Assemblies

0201 Discretes

A pareto analysis of the 142 defects observed on the 0201 discretes was performed and it was shown that the majority of the defects were caused by bridging of the components, followed by billboarding. When looking further at the analysis, 100% of the bridged resistors were found on the parts using Spacing “A”, the smallest defined discrete to discrete spacing clearance. The right-most image on Figure 11 shows an example of the observed 0201 bridging defects. All higher spacings in both solder mask defined and non-solder mask defined resulted in zero bridging defects. The billboard defects were primarily related to a pick-up error. Again, solder balls were observed on the SMD pad locations however were not identified as a defect.

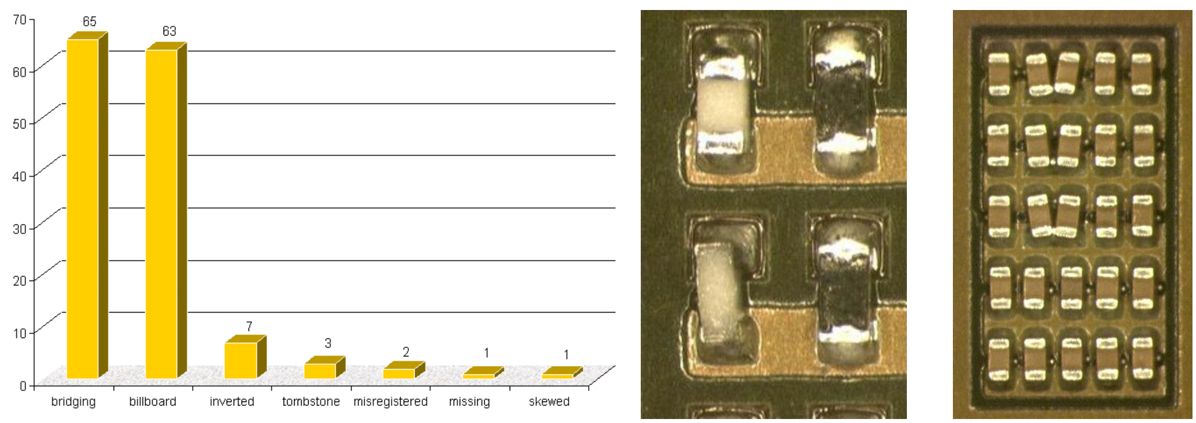
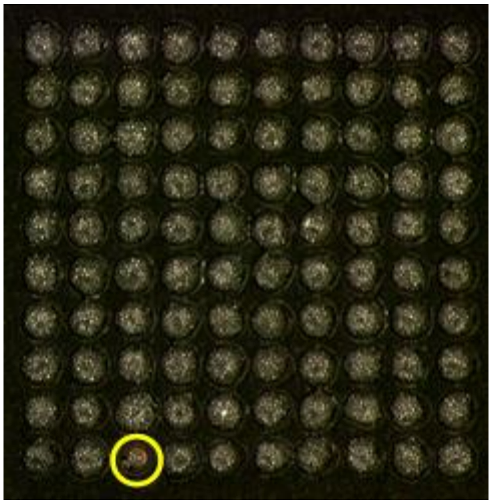


Figure 11 - (Left) Pareto of 0201 Defects. (Center) 0201s Inverted and Billboarded Defects. (Right) – 0201 Spacing “A” Bridging and Solder Balls

0.3mm Pitch CSPs

On the SPTV, there were four 100 I/O, 0.3mm CSPs on the panel, and two 368 I/O, 0.3mm CSPs. Small and large pad sizes, and NSMD and SMD pad combinations were used as per Table 2. The stencil apertures were all large, even for the small pad sizes (0.5 stencil area aspect ratio). For the small pad design, there was a risk of insufficient paste as shown by Figure 12 below circled in yellow.



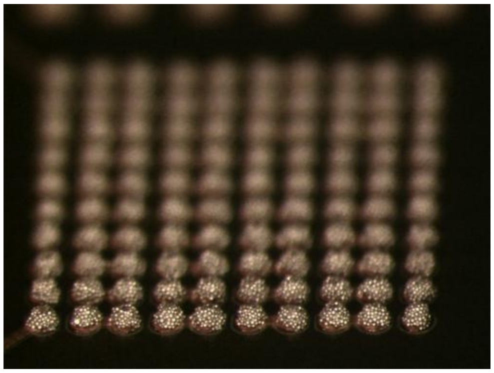


Figure 12 - (Left) 0.3mm CSP, NSMD Small Pad. (Right) 0.3mm CSP – NSMD Large Pad

From the build of 150 panels (100 in air, 50 in N2), the CSPs went through x-ray to detect the defects, as shown in Table 8 below, and excessive bridging was the obvious defect. The challenge is that any aperture smaller than the large size used, will be a challenge to screen print without getting too many insufficient defects. However, the large aperture (with a 4mil stencil) used gives too much paste.

Table 8 - CSP Defects in Air and Nitrogen Reflow Environment

Description	Mask	Board	Bridging (Air)	Bridging (Nitrogen)	Missing Balls	Open	Solder Balls
100 I/O WLCSP - 0.3 mm pitch	Large, NSMD	1	4	0	0	0	0
100 I/O WLCSP - 0.3 mm pitch	Large, SMD	2	5	0	0	0	2
100 I/O WLCSP - 0.3 mm pitch	Small, NSMD	3	27	4	0	2	0
100 I/O WLCSP - 0.3 mm pitch	Small, SMD	4	21	14	10	2	0
368 I/O Laminate CSP - 0.3 mm pitch	Small, NSMD	1	2	6	0	0	0
368 I/O Laminate CSP - 0.3 mm pitch	Small, SMD	2	43	42	0	0	0

Subsequently, a new stencil was ordered with varying aperture sizes in 0.5mil increments. A 1mil step down to a 3mil stencil thickness, with a small aperture was tried for one of the CSP locations as shown in Figure 13, but the step did not help to solve the problem.

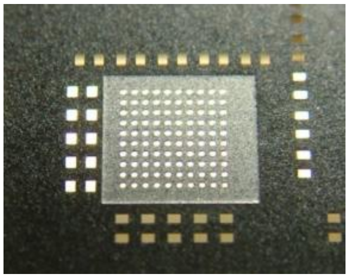


Figure 13 - Stencil Aperture with 1mil Step-down for 0.3mm CSP Location

From the experiment it was determined that a 0.5mil reduction to the aperture diameter could be made from the large aperture previously used. However, it is still unknown as to whether this is enough to eliminate the bridging defects, or whether a flux dipping process would be required. A follow-on build is planned to determine if it is possible to eliminate bridging defects on these 0.3mm pitch CSPs.

Component Spacing

Overall, the results of the component spacing DFM analysis were successful, based on the primary attach analysis. With exception to the Spacing "A" discrete to discrete spacing results, all other spacing variations had zero defects on the lowest level spacing. Figure 14 summarizes the results that were observed.

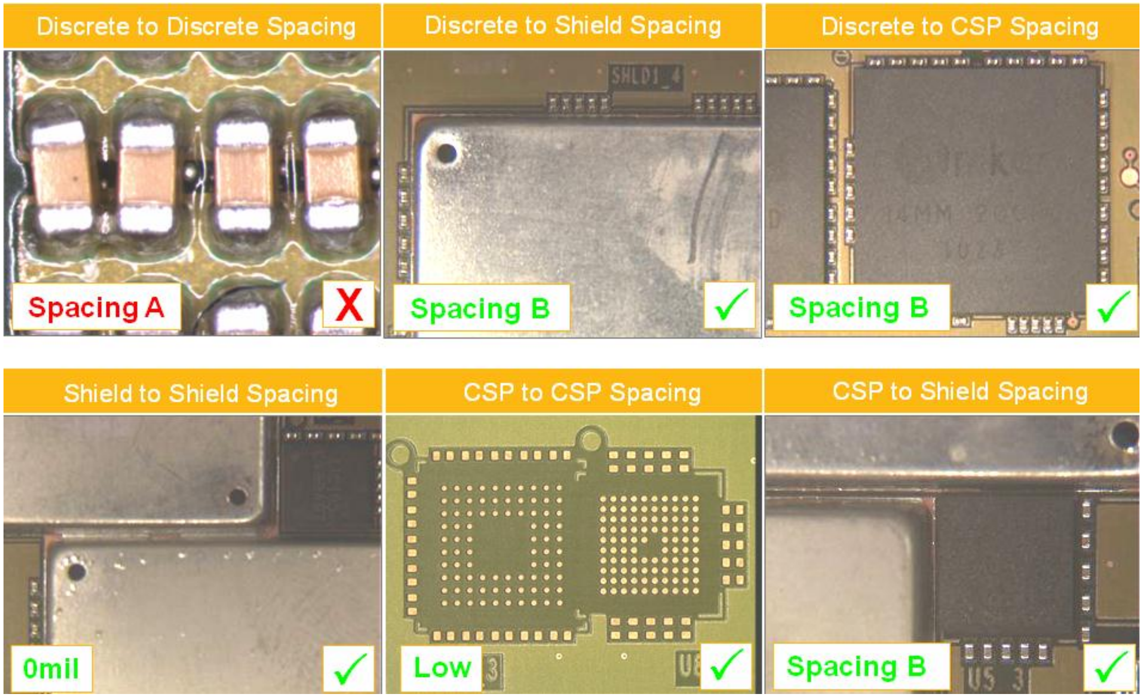


Figure 14 - Summary of Component Spacing Study

Conclusions

The assembly of the SPTV boards provided an opportunity to study many different process issues for manufacturing leading edge components found in handheld portables. We can establish the following conclusions based on data that has been gathered:

- For 01005s, elliptical solder mask defined pads yielded the best results from the variations studied. To place 01005s, there are many critical control requirements such as dust control, exact tolerances on printed circuit boards and stencil apertures. Automated equipment to inspect for the presence of 01005 paste deposits and component bodies must have precise program algorithms to validate such minute features.
- For 0201s, Spacing "B" and larger resulted in zero bridging defects in both SMD and NSMD land patterns. Bridging defects were found in the 0201s with the clearance of Spacing "A". 0201 billboarding defects found on this assembly were determined to be caused by pick-up errors during placement.
- For 0.3mm pitch CSPs, bridging defects were found on all variations reflowed in air. The large pad variations (in both NSMD and SMD) had less bridging defects than the small pad variations. In nitrogen reflow, no bridging defects were found on the large pad variations.
- For discrete to shield, discrete to CSP, shield to shield, CSP to CSP, and CSP to shield component spacing, the lowest level spacing had zero defects.

Future Work

A selection of test vehicle cards will be subjected to 500 cycles of accelerated thermal cycling (ATC) and the results will be analyzed and failure analysis will be conducted. A number of boards will be subjected to mechanical vibration and shock. Failure analysis will also be performed to assess the results from the mechanical testing. RF electrical signal measurements will be studied before and after ATC, vibration and shock testing to evaluate the effectiveness of the RF shields present on this test vehicle. An in-depth study of the primary and rework attach process of 01005 components will be studied. A build to study the screening process for 0.3mm pitch CSPs is planned to determine if bridging defects may be eliminated.

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DFM Rules for Smartphones: An Analysis of Yield on Extremely Dense Assemblies

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Toronto, Ontario, Canada

Agenda

- Introduction
- Test Vehicle Description
  - *Layout*
  - *Layout & Components*
  - *Details of DFM Features*
- Build Summary
- Results
  - *Paste Inspection Results*
  - *Assembly Yield Results*
    - *Solder Balls*
    - *01005 Discretes*
    - *0201 Discretes*
    - *0.3mm Pitch CSPs*
    - *Component Spacing*
- Conclusions

Introduction

- What is DFM and why do we need it?

- Why do smartphone designs violate traditional DFM guidelines?

- What does this paper focus on?
  - Determine which pad design provided the highest first-pass assembly yield for 01005 discretes and for 0.3mm pitch CSPs
  - Determine the minimum clearance between component types

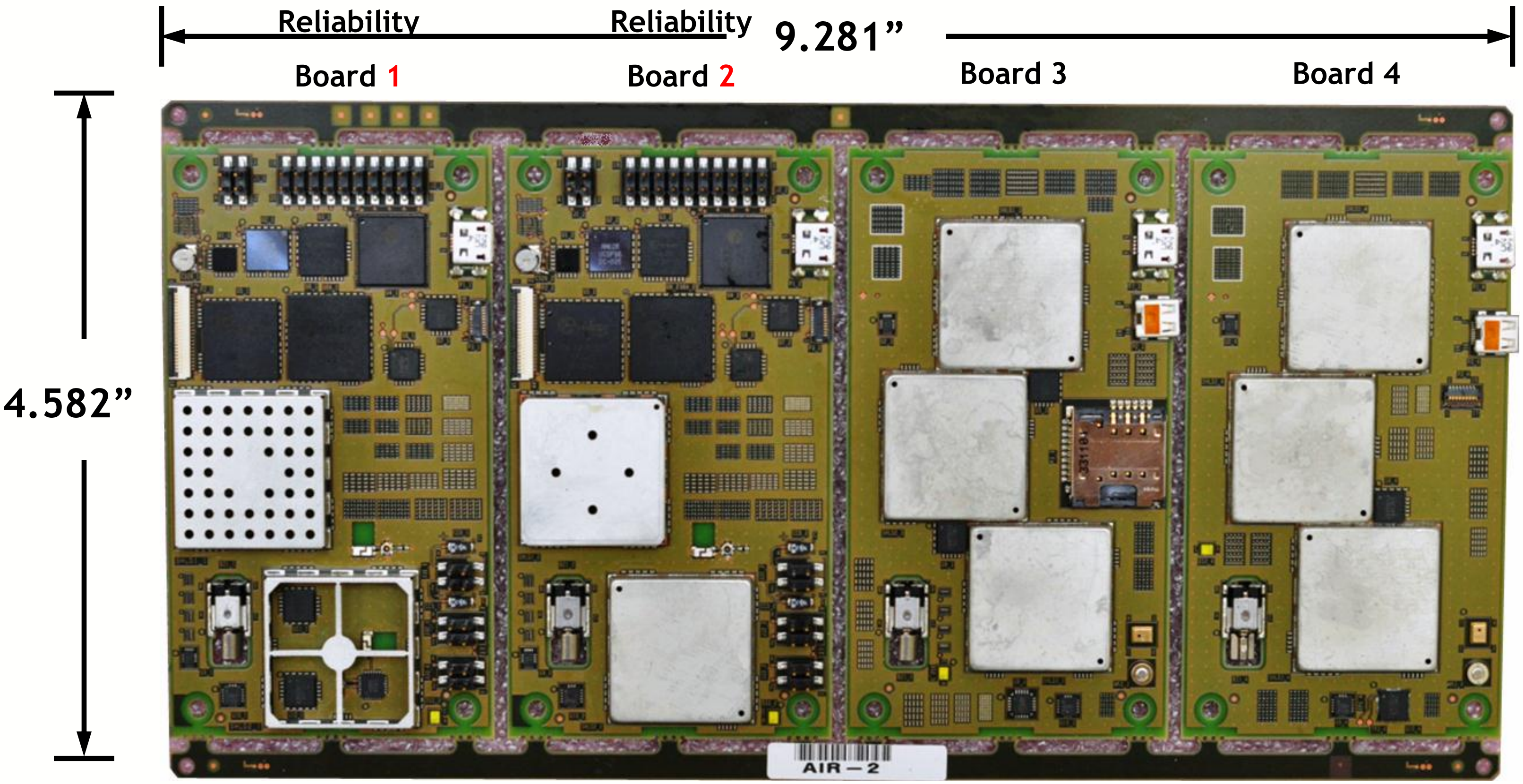
- What platform was used for this study?

Smartphone Test Vehicle
SPTV

Layout

Board Thickness: 0.040”

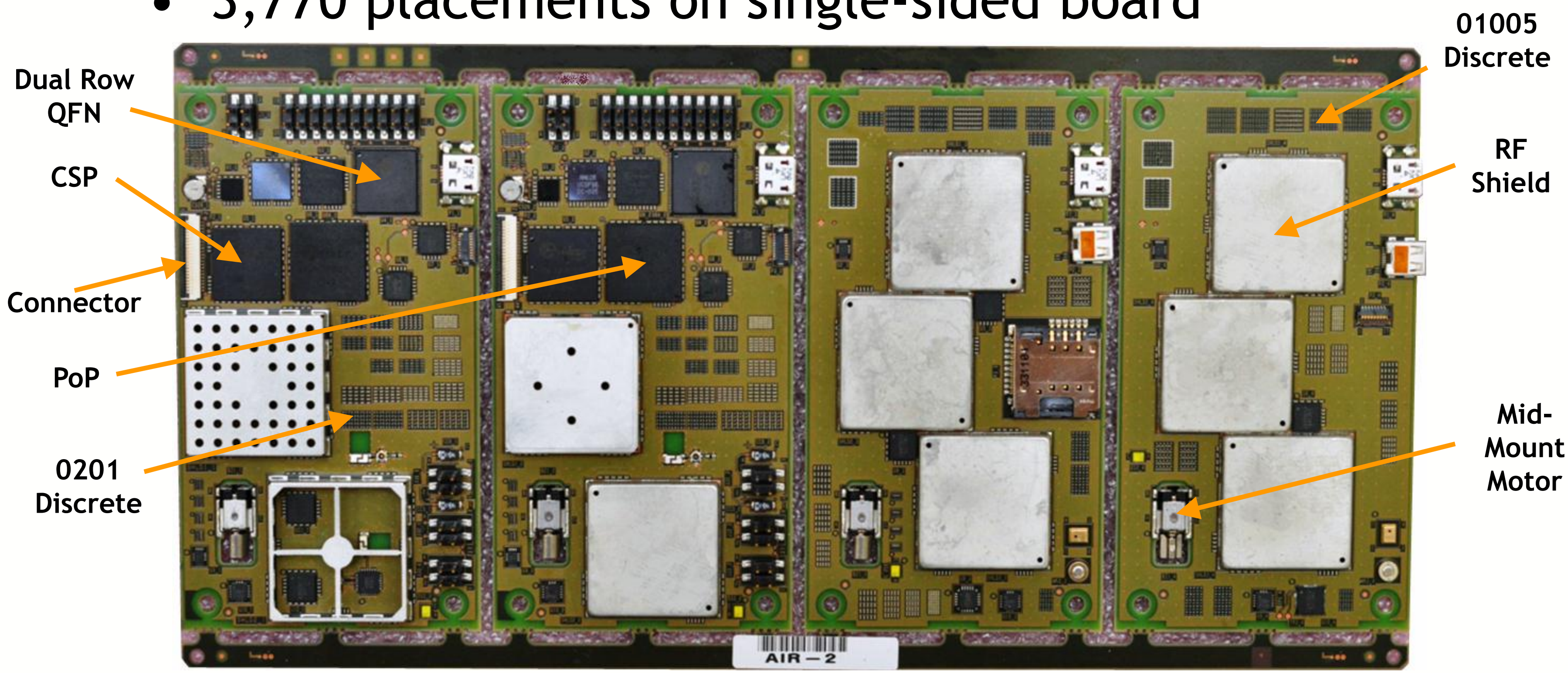
Surface Finish: OSP



Smartphone Test Vehicle SPTV

Layout & Components

- 48 different component types
- 3,770 placements on single-sided board

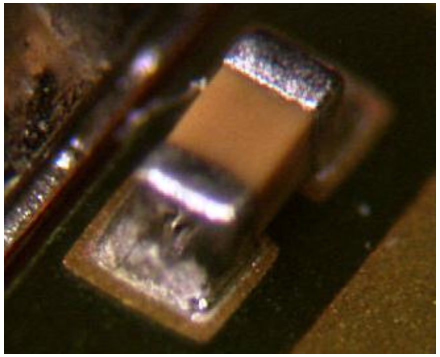


Test Vehicle Description

Details of DFM Features

- Pad designs for 01005 discretes and 0.3mm pitch CSPs
- Component Spacing:
  - Discrete to Discrete
  - Discrete to Shield
  - Discrete to CSP
  - CSP to Shield
  - CSP to CSP
  - Shield to Shield

Discretes Used:
0201 Capacitors



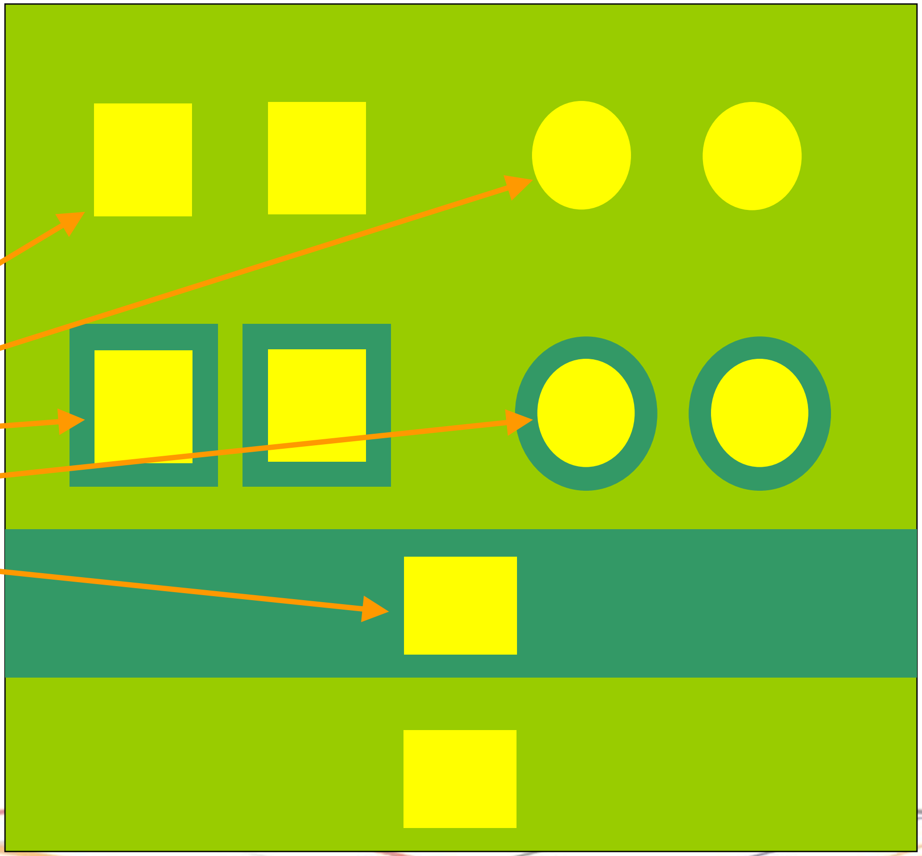
Test Vehicle Description

Details of DFM Features

- Pad designs for 01005 discretes:

01005 Discrete Pad Design Variations

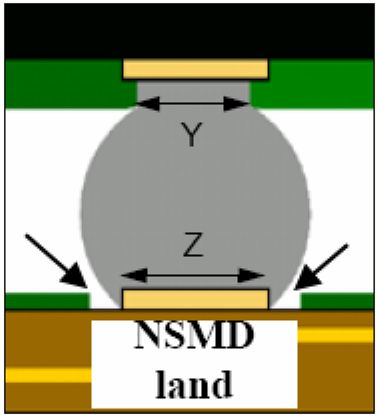
Shape	Solder Mask
Rectangular	Non Solder Mask Defined
Elliptical	Non Solder Mask Defined
Rectangular	Solder Mask Defined
Elliptical	Solder Mask Defined
Rectangular	SMD on one side, NSMD on the other



Test Vehicle Description

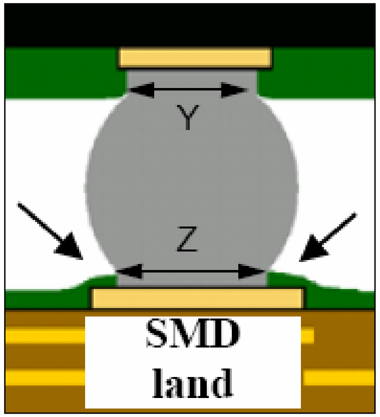
Details of DFM Features

- Pad designs for 0.3mm pitch CSPs:



0.3mm Pitch CSP Pad Design Variations

Pad Dimensions	Solder Mask
Small	Non Solder Mask Defined
Large	Non Solder Mask Defined
Small	Solder Mask Defined
Large	Solder Mask Defined



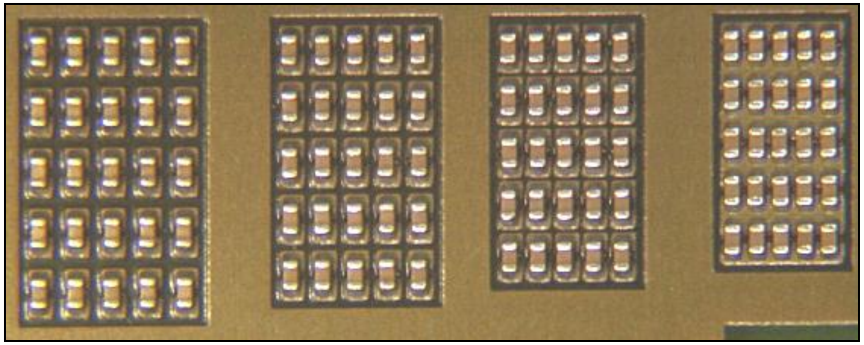
Test Vehicle Description

Details of DFM Features

- Discrete to Discrete Spacing Variations:

Discrete to Discrete Spacing Variations

Pad Definition	Spacing Between Devices
Solder Mask Defined	A (Smallest)
Solder Mask Defined	B
Solder Mask Defined	C
Solder Mask Defined	D (Largest)
Non Solder Mask Defined	B
Non Solder Mask Defined	C
Non Solder Mask Defined	D



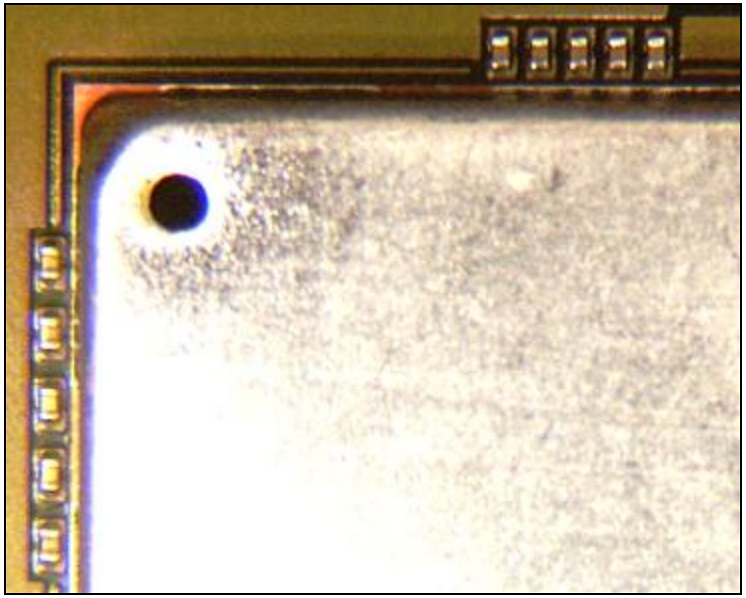
Test Vehicle Description

Details of DFM Features

- Discrete to Shield Spacing Variations:

Discrete to Shield Spacing Variations

Solder Mask	Spacing Between Devices
Non Solder Mask Defined	B
Non Solder Mask Defined	C
Non Solder Mask Defined	D
Solder Mask Defined	B
Solder Mask Defined	C
Solder Mask Defined	D



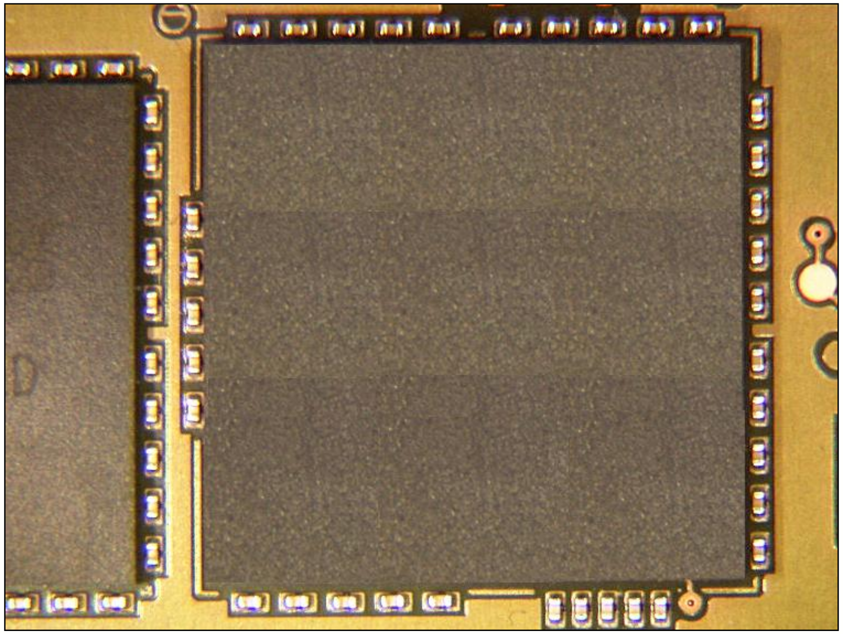
Test Vehicle Description

Details of DFM Features

- Discrete to CSP Spacing Variations:

Discrete to CSP Spacing Variations

Solder Mask	Spacing Between Devices
Non Solder Mask Defined	B
Non Solder Mask Defined	C
Non Solder Mask Defined	D
Solder Mask Defined	B
Solder Mask Defined	C
Solder Mask Defined	D



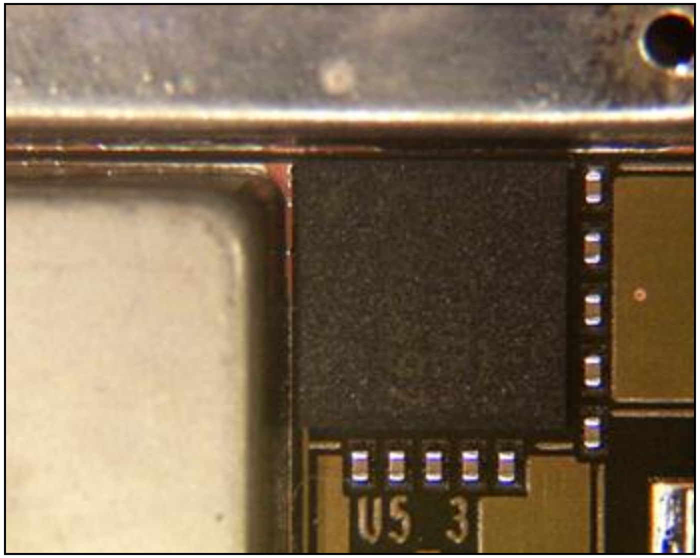
Test Vehicle Description

Details of DFM Features

- CSP to Shield Spacing Variations:

CSP to Shield Spacing Variations

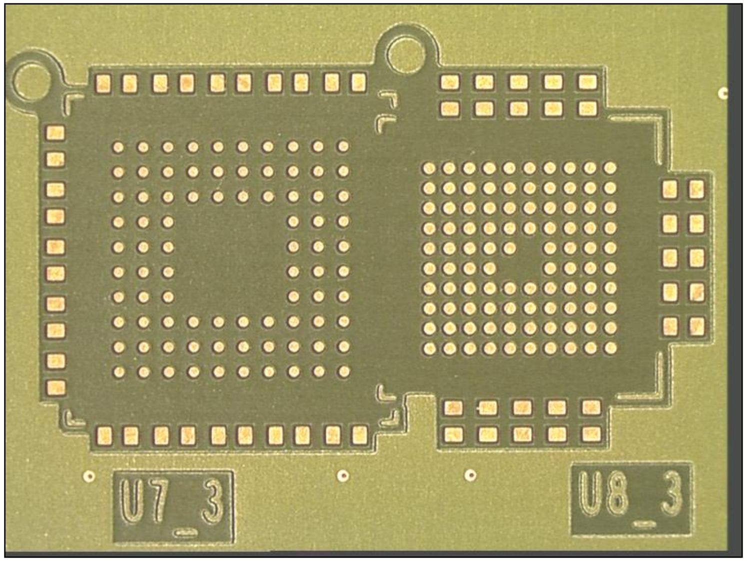
Solder Mask	Spacing Between Devices
Non Solder Mask Defined	B
Non Solder Mask Defined	C
Non Solder Mask Defined	D
Solder Mask Defined	B
Solder Mask Defined	C
Solder Mask Defined	D



Results

Details of DFM Features

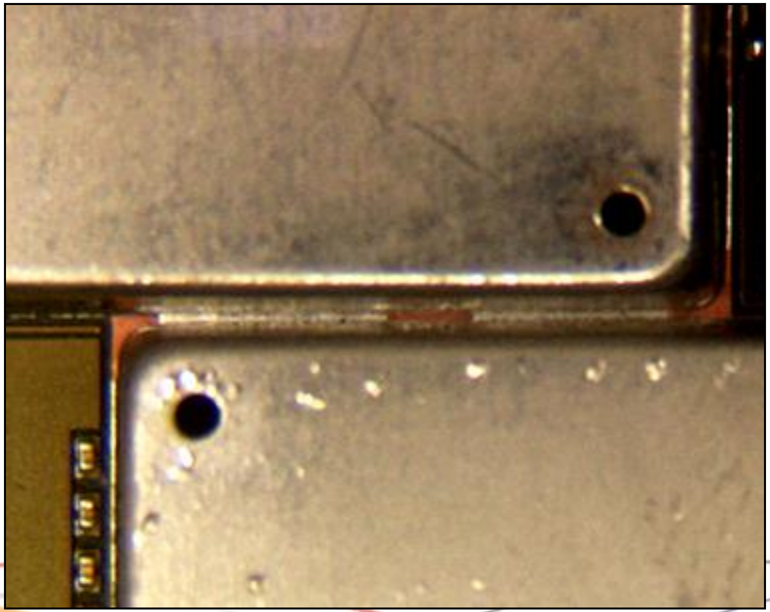
- CSP to CSP Spacing Variations:
  - 97 I/O 0.4mm pitch CSP and 84 I/O 0.5mm pitch components were used
  - 3 different spacing variations were studied that were 4 mils between each of the levels



Test Vehicle Description

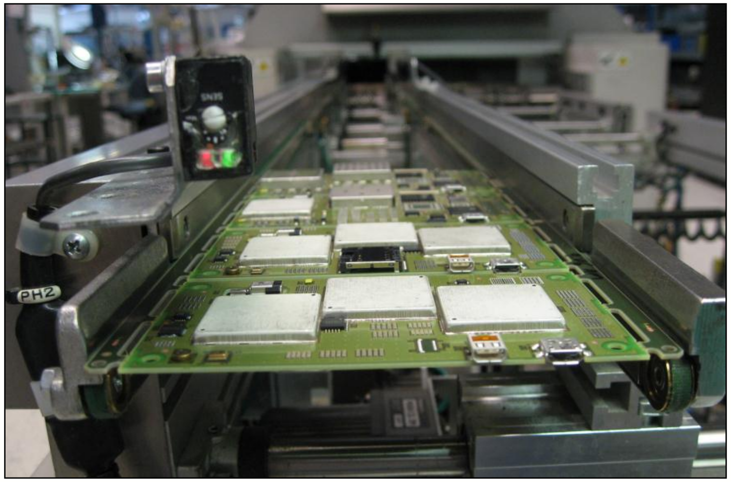
Details of DFM Features

- Shield to Shield Spacing Variations:
  - Spacing between 2 identical shields was studied
  - 4 spacing variations were designed into the SPTV
    - First spacing variation set at 0 mils
    - 3 remaining spacing variations were separated by 4 mils



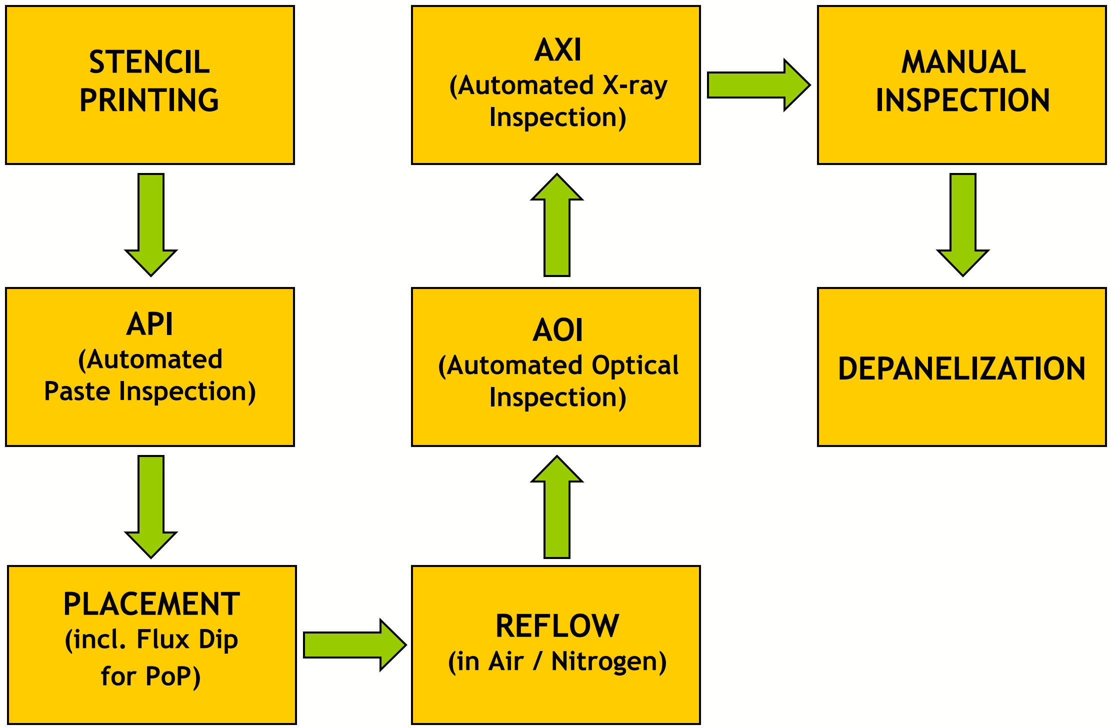
Build Summary

- Boards were built on a conventional SMT line
- Solder Paste – Type 4 halogen-free SAC305 no-clean
- Stencil – 0.004” (100μm) thick, electropolished and coated to facilitate paste release
- Package on Package component – top package dipped in no-clean flux in a linear dip fluxer



Build Summary

Process

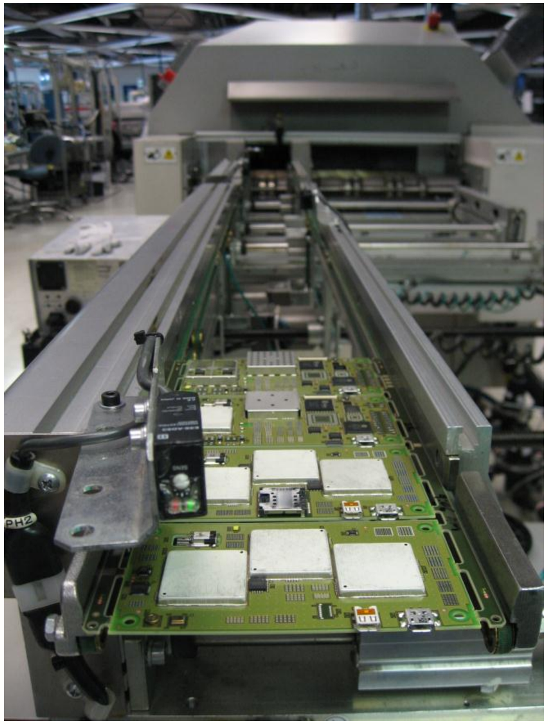


Build Summary

- Reflow Peak Temperatures: 235°C to 240°C
- Time Above Liquidous (217°C): 53 – 61 seconds

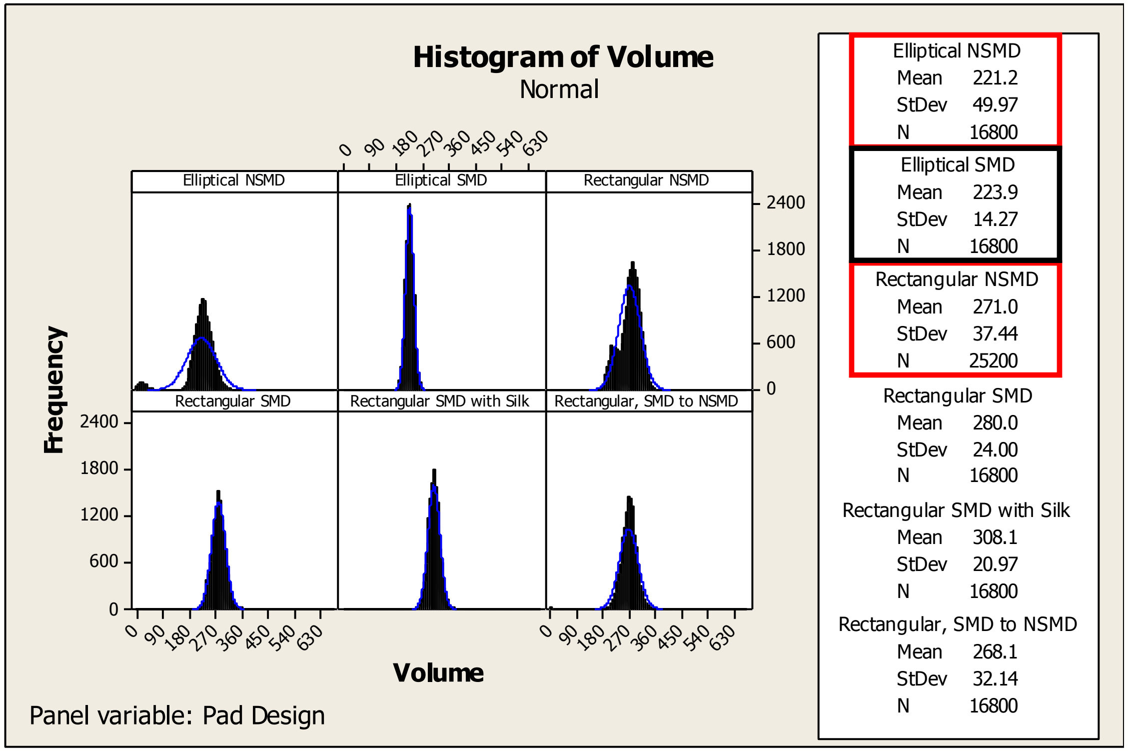
Build Plan Variations

Component Population	Build Qty	Reflow Environment
Boards fully populated	50	Air
Boards with unpopulated components	50	Air
Boards with unpopulated components	50	Nitrogen



Results

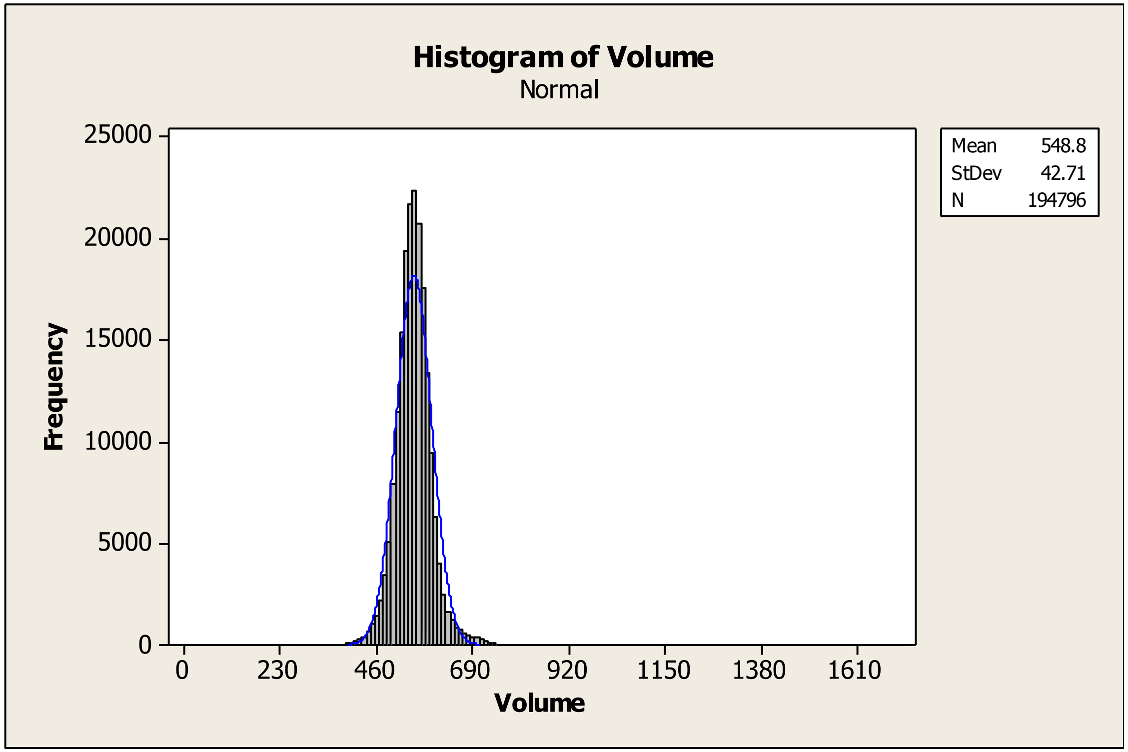
01005 Paste Inspection



- Elliptical and rectangular NSMD performed poorly (insufficient defects)
- SMD pads performed the best especially the elliptical SMD land design

Results

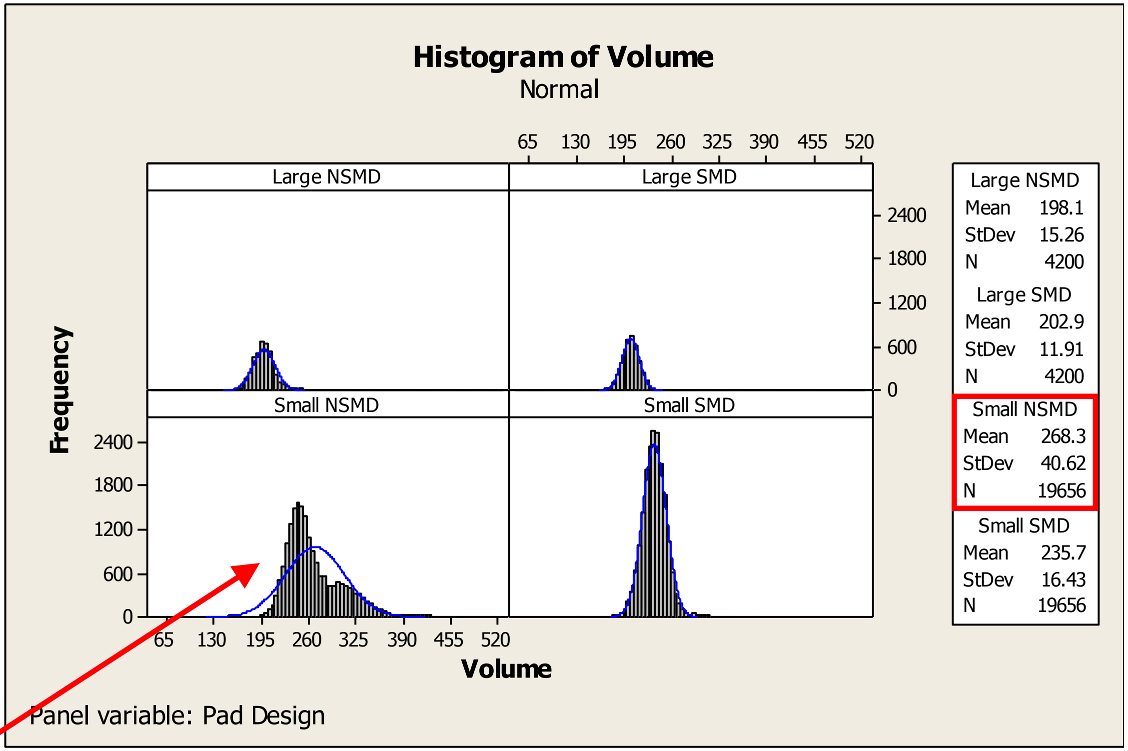
0201 Paste Inspection



- Solder paste volume was within desired limits
- No issues were seen from the solder paste prints

Results

0.3mm Pitch CSP Paste Inspection



- NSMD small pads printed the worst
- Larger sized stencil apertures were used for both the small and large pad designs which resulted in excess solder

Results

Assembly Yield

- Assembly yield for 150 panel build:

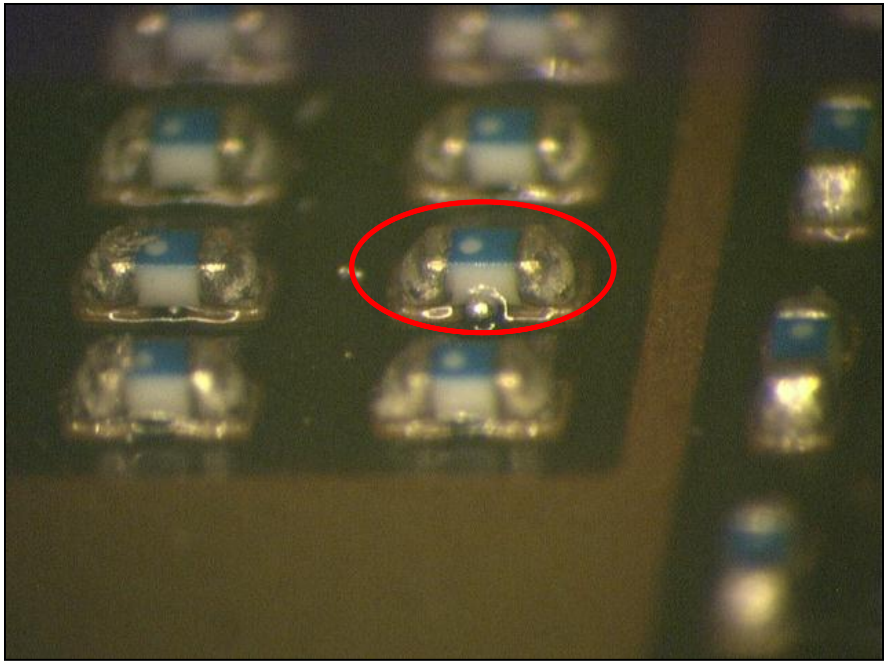
Part Type	Visual Defects	X-Ray Defects	Opportunities	PPM
0.3mm CSP	1	172	600	288,333
0201	142	0	348,000	408
01005	6	0	195,000	31

- Defects include standard features and DFM features
- Solder balls were observed however none were large enough to be defects according to IPC-610E

Results

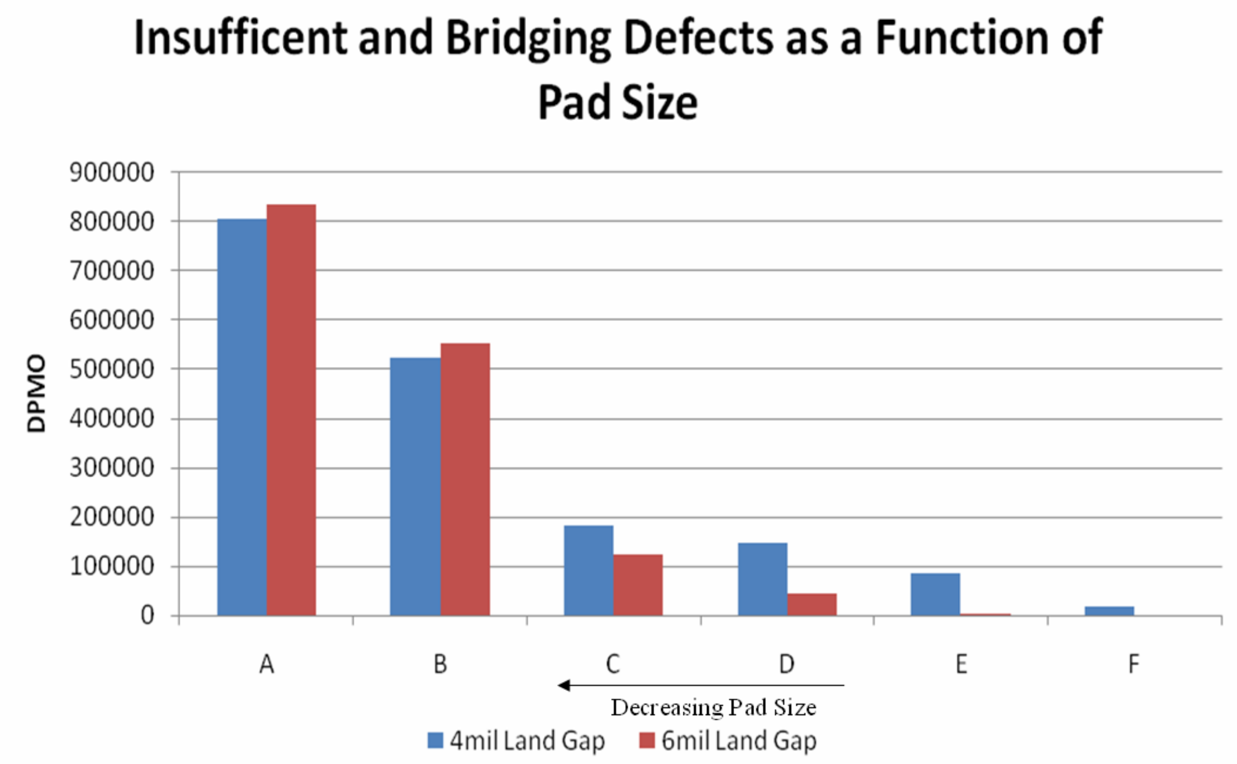
Solder Balls

- 3 panels assembled in air were randomly selected and counted for solder balls
- Average of 944 solder balls per panel (found near 01005s and 0201s)
- 91% of solder balls were located adjacent to discrete components assembled on SMD pads
- 9% of solder balls located near NSMD pads



Results

01005 Discretes

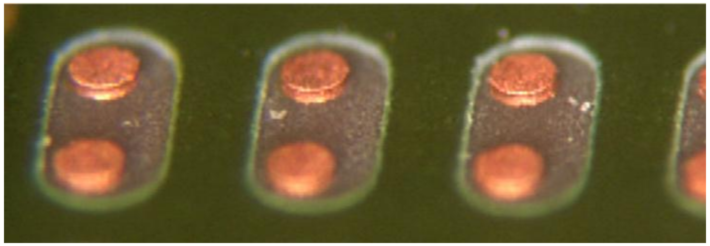


- Pad size F has an Area Aspect Ratio of 0.53 (traditional target >0.66)

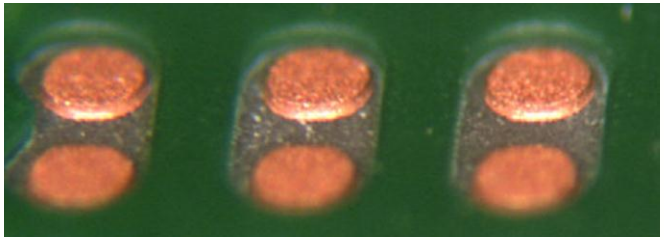
Results

01005 Discretes

01005 Pad from Supplier A



01005 Pad from Supplier B



- Supplier A pads were over-etched by as much as 2 mils
- Supplier B pads were under-etched by 0.5mils
- 150 panel build used Supplier A boards

Results

01005 Discretes

- Pad solder paste results using Supplier A boards:

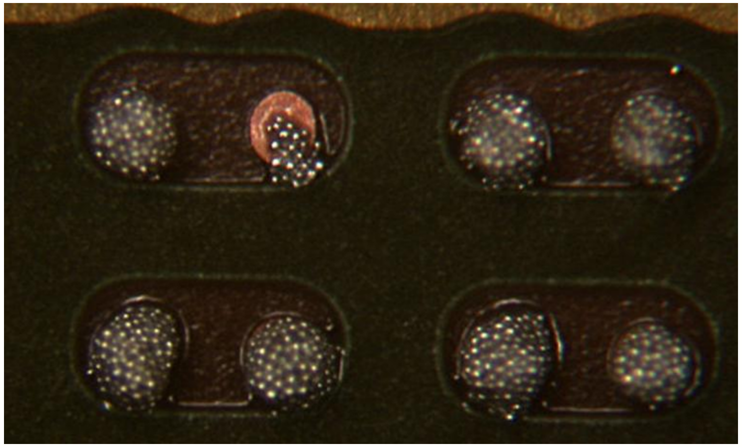
Pad Type	Total Pads	<Lower Limit	>Upper Limit	PPM
Rectangular, SMD	16800	7	0	417
Rectangular, NSMD	25200	45	2	1,865
Elliptical, SMD	16800	0	0	0
Elliptical, NSMD	16800	686	0	40,833

- Elliptical SMD pad type performed the best
- NSMD pad types performed the worst

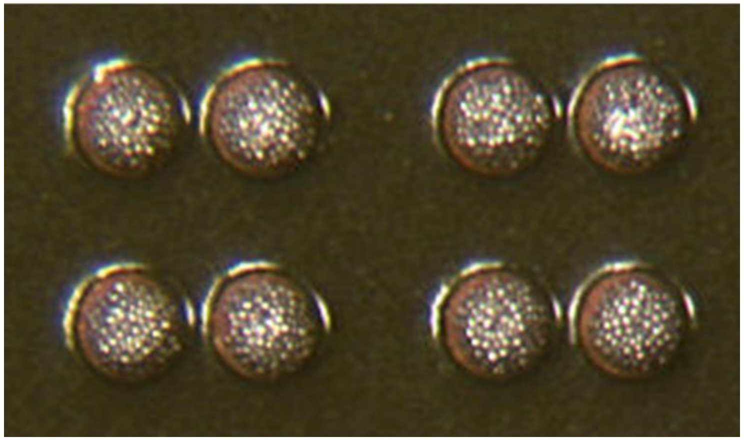
Results

01005 Discretes

Supplier A Elliptical NSMD Pads



Supplier A Elliptical SMD Pads

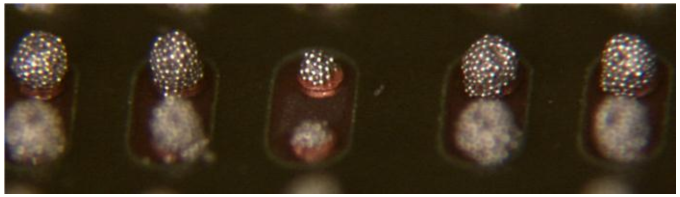


- Supplier A elliptical SMD pads had more consistent paste deposits

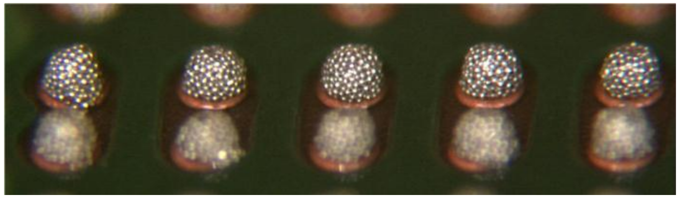
Results

01005 Discretes

Supplier A (Over-Etched Copper)



Supplier B (Correct Copper Size)



- Supplier B elliptical NSMD solder paste deposits were more consistent than the deposits found on Supplier A panels

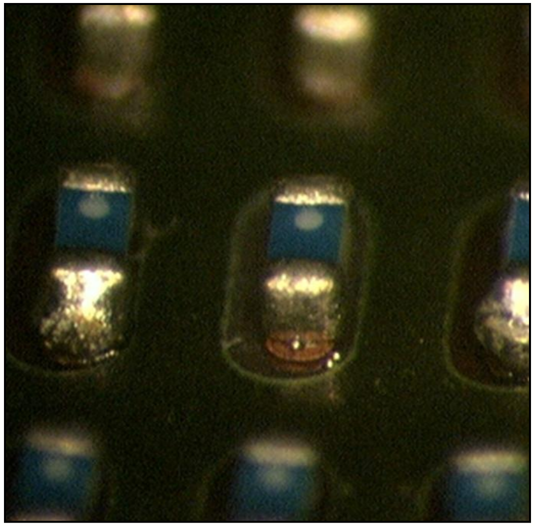
Results

01005 Discretes

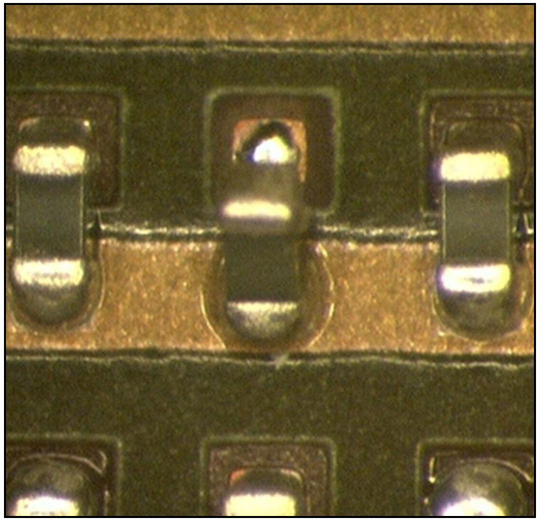
- Out of 195,000 01005 placements, 8 defects were found during the inspection process:

Missing Component Defect, Qty=1

Insufficient Paste Defect, Qty=1



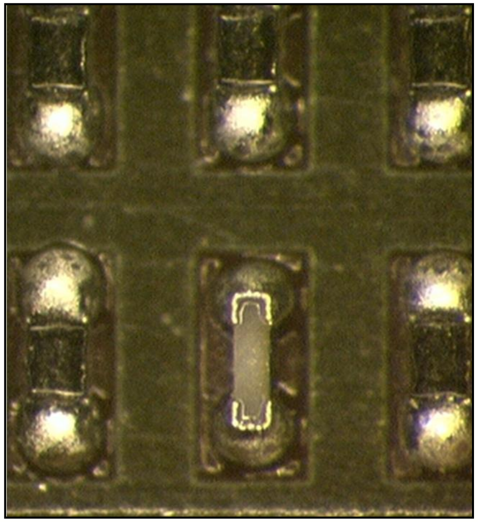
Tombstone Defect, Qty=4



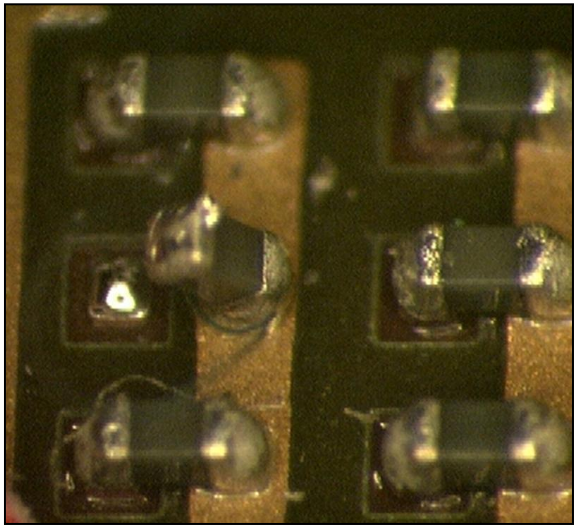
Results

01005 Discretes

Billboard Defect, Qty=1

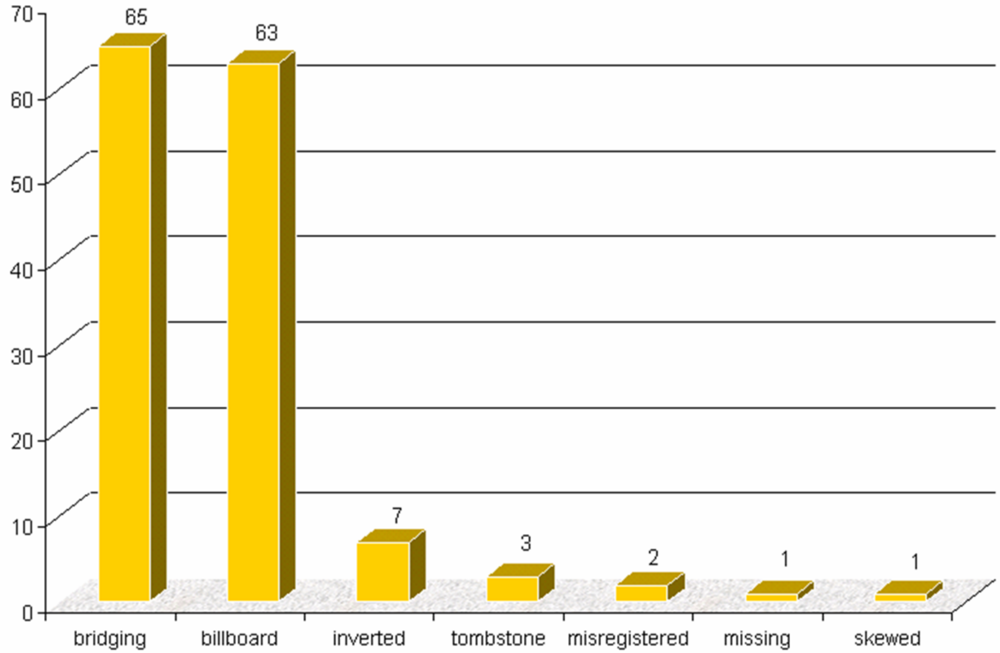


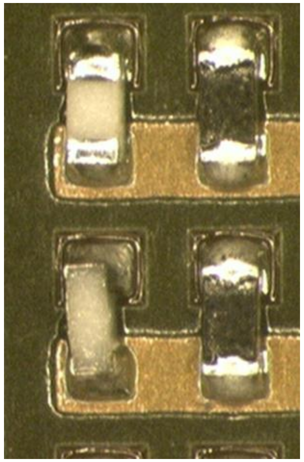
Dust Fiber Defect, Qty=1



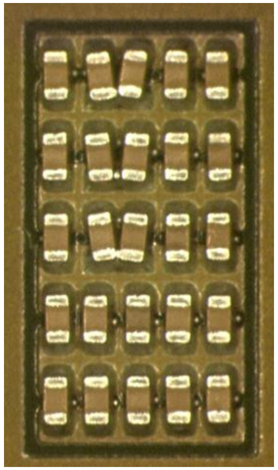
Results

0201 Discretes





0201 inverted and Billboard Defects



0201 Spacing "A" Bridging and Solder Ball Defects

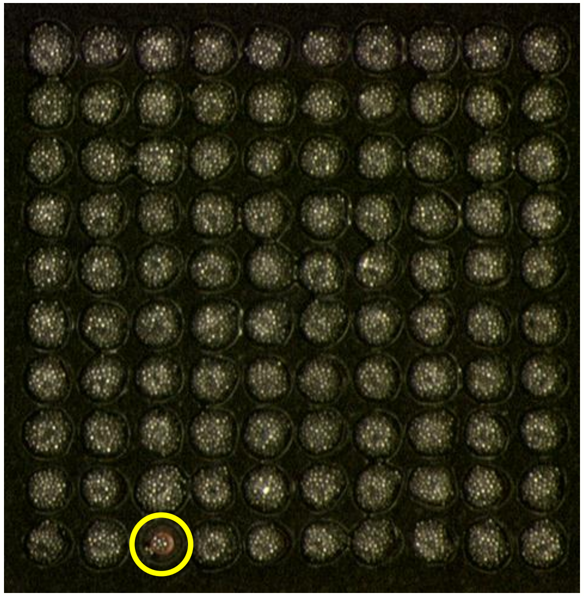
- Pareto of 0201 defects, qty=142
- Majority of the defects caused by bridging on Spacing "A"
- All higher spacings in both SMD and NSMD resulted in zero bridging defects

Results

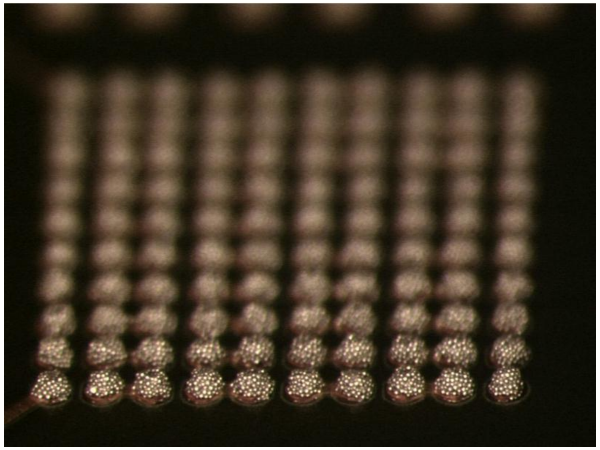
0.3mm Pitch CSPs

- On SPTV, 0.3mm pitch CSPs : Qty=4 of 100 I/O , Qty=2 of 368 I/O
- Small and large pad sizes, NSMD and SMD pad combinations were used
- Large stencil apertures were used for all locations

0.3mm CSP – NSMD Small Pad



0.3mm CSP – NSMD Large Pad



Results

0.3mm Pitch CSPs

- Defects detected by x-ray in air and nitrogen reflow environments:
(150 panels built – 100 in air, 50 in Nitrogen)

Description	Mask	Board	Bridging (Air)	Bridging (Nitrogen)	Missing Balls	Open	Solder Balls
100 I/O WLCSP - 0.3 mm pitch	Large, NSMD	1	4	0	0	0	0
100 I/O WLCSP - 0.3 mm pitch	Large, SMD	2	5	0	0	0	2
100 I/O WLCSP - 0.3 mm pitch	Small, NSMD	3	27	4	0	2	0
100 I/O WLCSP - 0.3 mm pitch	Small, SMD	4	21	14	10	2	0
368 I/O Laminate CSP - 0.3 mm pitch	Small, NSMD	1	2	6	0	0	0
368 I/O Laminate CSP - 0.3 mm pitch	Small, SMD	2	43	42	0	0	0

- Any aperture smaller than what was designed, is a challenge to screen print without yielding many insufficient defects
- Any aperture larger than what was designed, would result in excessive paste

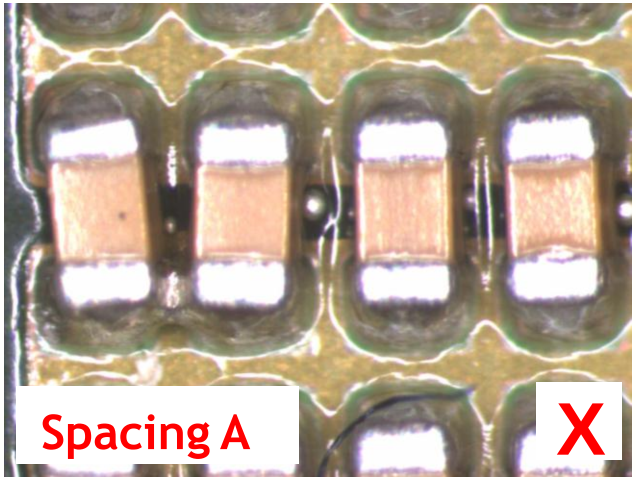
Results

Component Spacing

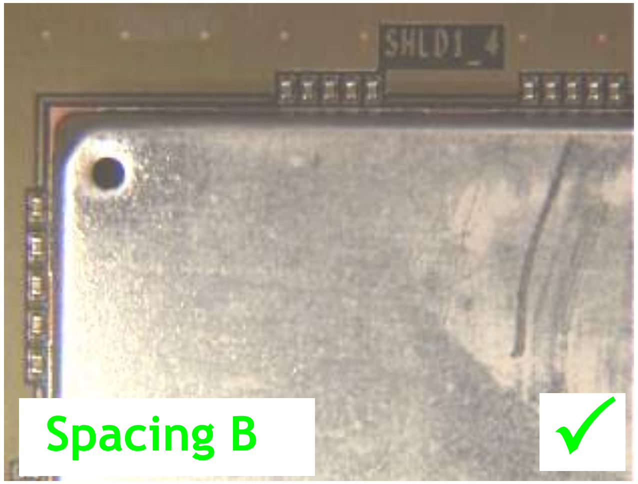
- Results of the component spacing DFM analysis were successful

- All spacing variations had zero defects on the lowest level spacing except Spacing “A” discrete to discrete variation

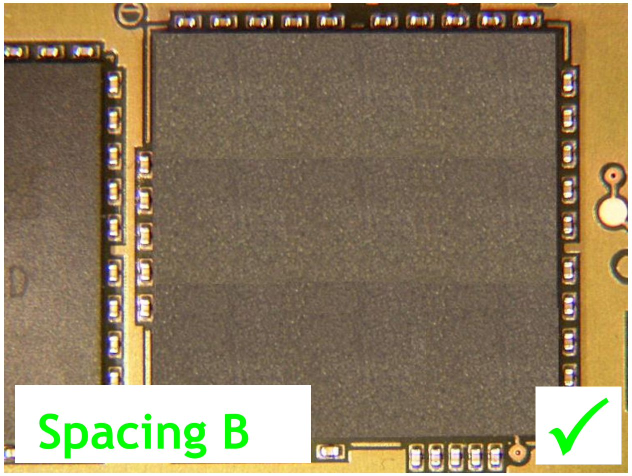
Discrete to Discrete Spacing



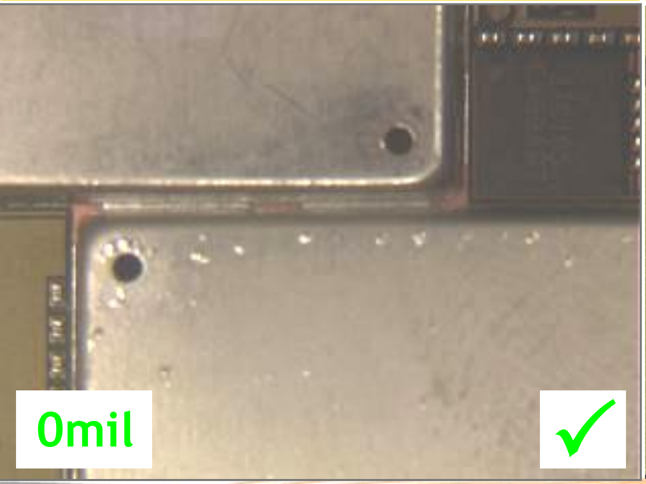
Discrete to Shield Spacing



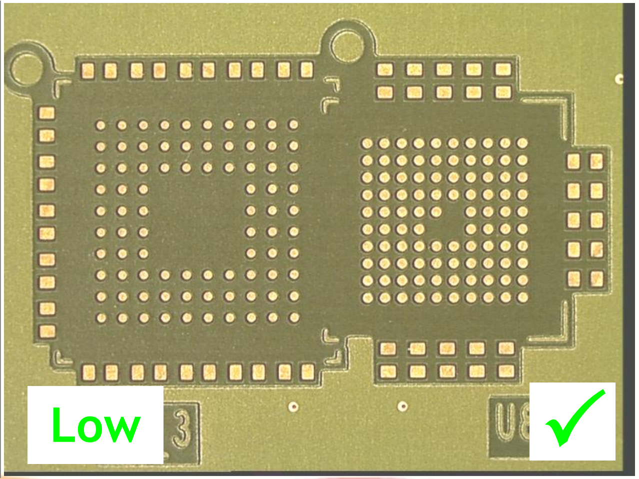
Discrete to CSP Spacing



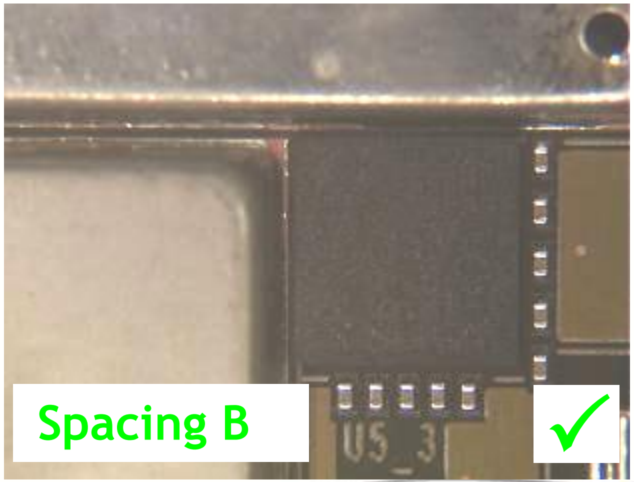
Shield to Shield Spacing



CSP to CSP Spacing



CSP to Shield Spacing



Conclusions

- For 01005s:
  - Elliptical solder mask defined pads yielded the best results from the variations studied
  - Many critical control requirements include dust control, exact tolerances on PCBs and stencil apertures
  - Automated equipment to inspect for the presence of 01005 paste deposits and component bodies must have precise program algorithms to validate such minute features

Conclusions Continued

- For 0201s:
  - Spacing “B” and larger resulted in zero bridging defects in both SMD and NSMD land patterns
  - Bridging defects were found with the clearance of Spacing “A”
  - Billboarding defects found on this assembly were determined to be caused by pick-up errors during placement

Conclusions Continued

- For 0.3mm pitch CSPs:
  - Bridging defects were found on all variations reflowed in air
  - Large pad variations (in both NSMD and SMD) had less bridging defects than the small pad variations
  - In nitrogen reflow, no bridging defects were found on the large pad variations

Conclusions Continued

- For Component Spacing:
  - No defects were found in the lowest level spacing for the following: Discrete to shield, discrete to CSP, shield to shield, CSP to CSP, and CSP to shield component spacing

Future Work

- Boards will be subjected to 500 cycles of accelerated thermal cycling (ATC) and the results will be analyzed and failure analysis will be conducted

- Boards will be subjected to mechanical vibration and shock and failure analysis will also be performed

- RF electrical signal measurements will be studied before and after ATC, vibration and shock testing to evaluate the effectiveness of the RF shields present on this test vehicle

- Study of the primary and rework attach process of 01005 components will be studied

- Study the screening process for 0.3mm pitch CSPs is planned to determine if bridging defects may be eliminated

Acknowledgements

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Thank you

Solid partners. Flexible solutions.