Nondestructive Inspection of Underfill Layers Stacked up in Ceramics-Organics-Ceramics Packages with Scanning Acoustic Tomography (SAT)

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Abstract

Ceramics packages are being used in the electronics industry to operate the devices in harsh environments. In this paper we report a study on acoustic imaging technology for nondestructively inspecting underfill layers connecting organic interposers sandwiched between two ceramics substrates.

First, we inspected the samples with transmission mode of scanning acoustic tomography (SAT) system, an inspection routine usually employed in assembly lines because of its simpler interpretation criteria: flawed region blocks the acoustic wave and appears darker. In this multilayer sample, this approach does not offer the crucial information at which layer of underfill has flaws. To resolve this issue, we use C-Mode Scanning in reflection mode to image layer by layer utilizing ultrasound frequencies from 15MHz to 120MHz. Although the sample is thick and contains at least 5 internal material interfaces, we are able to identify defective underfill layer interfaces.

Keywords: Ceramics Packages, Nondestructive Inspection, Ultrasound Imaging, SAT, C-Mode Acoustic Scanning, Underfill, Quality.

Introduction

Since introduction of Scanning Acoustic Tomography (SAT) also known as C-Mode Scanning Acoustic Microscopy (CSAM) technology to the semiconductor package manufacturing for more than two decades, several thousands of these equipment have been serving the industry as essential quality assurance tool. Acoustic imaging offers inspection of imperfect material joints containing non-metal structures, such as delamination between silicon-metal joint glues, which in turn are difficult if not impossible to detect with X-ray imaging approach. Therefore, the device package failure analysis engineers routinely utilize both x-ray and acoustic imaging technologies as their complimentary nondestructive analysis tools.

The SAT technology does have its own limitations derived from the physical nature of acoustical wave: requirement of liquid medium to transfer ultrasound energy, requirement of flat and smooth package surface, difficulty in designing transducers, low resolution at lower ultrasound frequencies, less penetration at higher ultrasound frequencies, and slow acquisition speeds, etc.

To extend these limitations to their ends, development of new transducers or probes with applicable frequency range from 50MHz to 300MHz are very crucial, along with other signal handling advancements.

Recently, Kitami, et al., reported development of a specially designed signal processing unit and high resolution probes that can image 1μm features engraved in silicon material, [1]and an echo gating technique that intelligently tracks the surface plane so that it drastically reduces invisible area due to rough exterior surfaces of the package.[2]

Encouraged by these new developments, we conducted a case study of SAT and X-ray CT imaging for a multilayer package consisting of two ceramics with flip-chip packages on organics substrates in between. The SAT system available for this study is also equipped with high resolution unit that generates well compressed pulses with excellent signal to noise ratio in a wide range of probe frequencies. In this report, we describe how flaws around flip-chip substrates embedded in a thick stack of ceramics mounted with surface components can be nondestructively inspected layer by layer to pinpoint the manufacturing defects hidden in them.

Experimental

On the manufacturing floor, we noticed that some of the multilayer devices electrically failed but they were also unable to find out the root cause using existing analytical equipment. Cross sectioning the sample is the only option which is not only destructive but also time consuming just to find out about the flaws along one line out of entire surface. Therefore, we selected to study the most acoustically complex device to investigate the capability with state of the art X-ray and ultrasound imaging technologies.

Sample Descriptions and Preview

The sample consists of high temperature co-fired ceramics (HTCC) substrates as top and bottom layers embedded with chip packages on polymer substrates in between as illustrated in Figure 1. The dimensions are 18mm width, 35mm length, and 3.3mm height. The regions of interest for possible delamination or voids are the joints to each interfaces between deep layers. Of course, these HTCC layers themselves are multi-layered substrates as well.

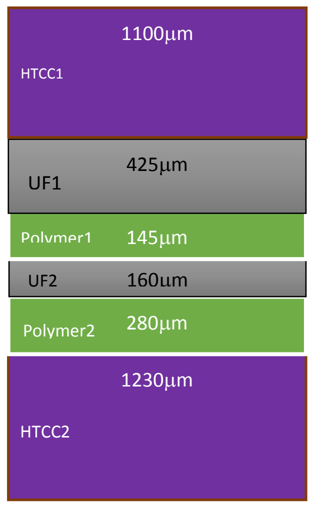

Figure 1. Illustration of material structure of the sample and their thickness in micrometer. Outer layers are high temperature co-fired ceramics.

So far we have accumulated some knowledge on computed tomography (CT) inspection of various complex structures, [3,4] especially for solder joints with good and clear CT images. This ceramics package, however, was just quickly viewed with an X-ray CT system to find out any flaws in metal features and ceramics layers.3D-CT inspection revealed that there are no apparent flaws in the material layers themselves; but no further attempts were made with CT inspection because it is difficult to observe delamination type of flaws between materials given the nature of X-ray beam that can easily penetrate such a flaw without significant intensity reduction. Comprehensive study with X-ray CT maybe needed elsewhere.

SAT Imaging

During manufacturing process at the beginning, the samples were inspected with available CSAM system without much success, pointing at that complicated sample structure; eventually requiring destructive cross sectioning. For nondestructive inspection, it is challenging to construct acoustic image of multilayer structures, because the echoes usually involve multiple reflections as well as their interferences. The difficulty increases when the sample is thicker as it requires lower frequency acoustic beam with smallest possible beam spot at longer focal lengths to reach deep layers. To overcome these hurdles, we need to get optimized transducers, [5]suitable to this particular sample.

All SAT results presented in this paper are from a new SAT system with high resolution unit option. This new SAT system has better capabilities covering transducer frequencies from 5MHz to 300MHz at prescribed frequencies, and especially with high resolution hardware option user can virtually set any desired ultrasound frequencies that should fit to a particular sample conditions.

As preliminary inspection, we used lower frequency probes to image different layer interfaces and try to identify them with their pattern appearances. A 50MHz, 7mm focal length probe was used to image the underfill layers UF1 and UF2 simultaneously with 2 echo gates. Figures 2 show these images acquired by focusing upper underfill level UF1.

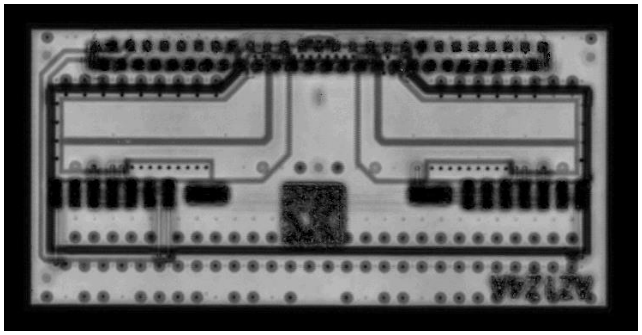

Figure 2(a). Image of Underfill layer 1 focused with a 50MHz probe frequency. This layer includes solder ball connections between adjacent layers. The big square shadow is laser marking and smaller rectangular shadows are surface mounted components.

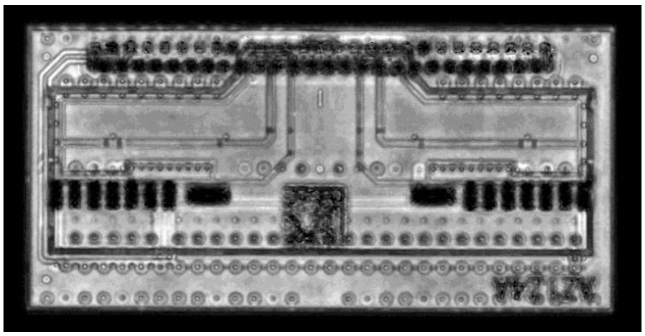

Figure 2(b). Image of Underfill layer 2 acquired by focusing upper UF1 layer.

After confirming solder balls of UF1, the focus target layer is shifted to lower level of second underfill layer UF2. The resultant images are shown in Figures 3 (a) and (b) in which we can clearly observe circuit patterns of the interface. These initial results encouraged us to proceed with this focal length probe, we can attain images of desired levels to find their flaws.

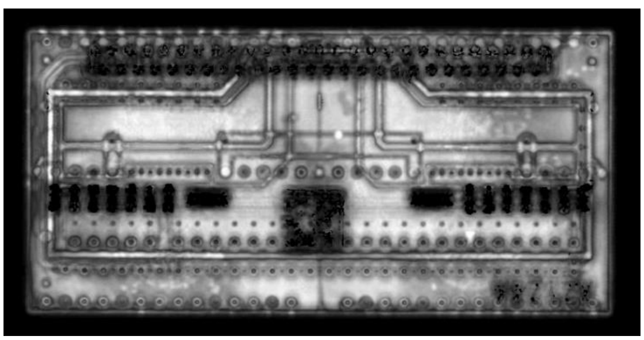

Figure 3(a). Image of Underfill layer 1 with a 50MHz probe frequency. This layer is not in focus.

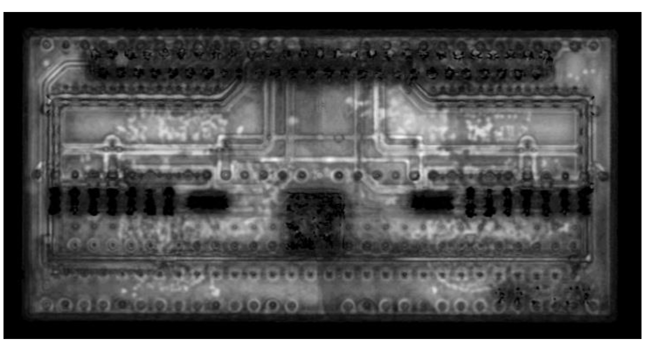

Figure 3(b). Image of Underfill layer 2 with a 50MHz probe frequency focused right at this layer. Features of UF2 surface patterns can be seen more clearly at this focus condition.

When inspecting with SAT system, we prefer to use higher frequency probing for two reasons: improvements of image lateral resolution and better separation of layers or depth resolution. Therefore, we gradually increase the probe frequencies to 75MHz, 90MHz, and 120MHz above in 1MHz step until the penetration depth cannot reach to the surface of HTCC2 layer.

With similar focus conditions as in 50MHz imaging, 100MHz probe frequency is used to acquire the images as shown in Figures 4. With possible highest frequency, the SAT image quality improved in contrast as well as better resolutions in all x, y, and z directions. As we expect to gain clearer layer separation with higher frequency probing, we can now open up more echo gates for detail analysis which we will describe in the next section.

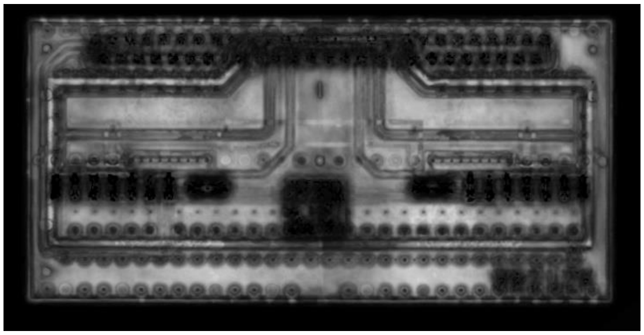

Figure 4(a). Image of Underfill layer 1 with a 100MHz probe frequency. This layer is not in focus.

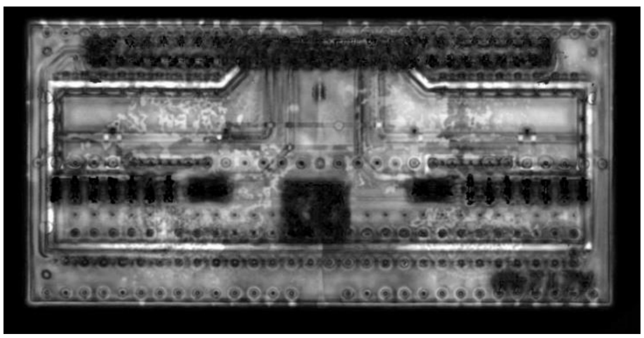

Figure 4(b). Image of Underfill layer 2 with a 100MHz probe frequency focused right at this layer. Features of UF2 surface patterns can be seen more clearly in better contrast.

Image Inspection & Analysis

In acoustic image analysis routine, one popular method of finding flaws is to scan the sample in the transmission mode. In this mode, a transducer is placed at one side of the sample to transmit ultrasound signals and another transducer from opposite side listens the sound as it gets through all sample layers. If the lattices of the materials in the sample are mechanically connected and ultrasound energy is allowed to be transported, a portion of transmitted ultrasound gets through the sample, or otherwise the sound is blocked by the flaws such as voids and delamination. Therefore, the scanned image is quite straightforward to interpret: the sample under test is good when the pass–through sound intensity is high, or the image is bright, relative to flawed region that will appear dark.

In Figures 5(a) and (b), transmission images of the sample inspected by using 15MHz and 25MHz transmission probes are shown.

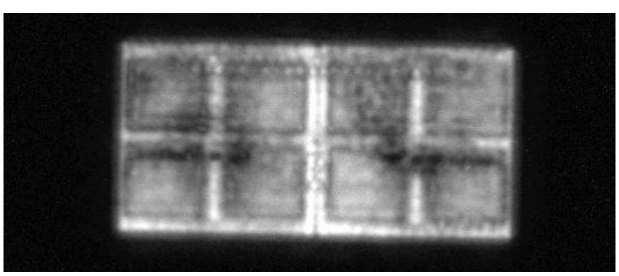

Figure 5(a) Through transmission scan with 15MHz

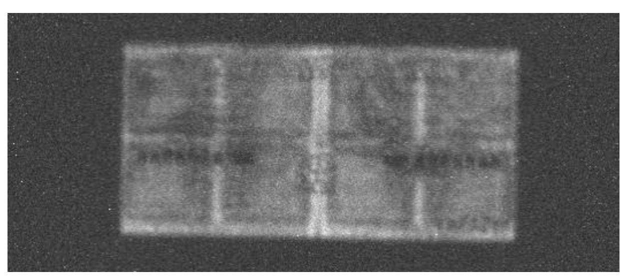

Figure 5(b) Through transmission scan with 25MHz

As seen in Figures 5, a through scan image quality is normally inferior to reflected echo image for several reasons. To penetrate a sample composed of organic compounds, lower frequency ultrasound must be used because more than 35MHz sound wave will be very difficult to penetrate most materials used in electronic packaging. A lower frequency (15MHz) unfocused probe will only offer low resolution images because their beam spot cannot be made small enough. Furthermore, though scan images do not offer layer specific layer information because transmitted sound wave have poor time resolution compared to the waveforms available in reflection mode. Therefore, this method is not appropriate for analyzing current sample that has several material layer interfaces, where we would like to find out about their flaws.

As we sweep probe frequencies from 50MHz to 120MHz for C-scan, best highest frequency for the sample is found to be around 100MHz at source. Therefore, we decided to employ this particular frequency in order to split layer interfaces and image them in a multi-gate setup. Figure 6 is the sample structure illustration and its associated actual echo waveform (A-scan) at 100MHz captured with 4GHz digital sampling rate.

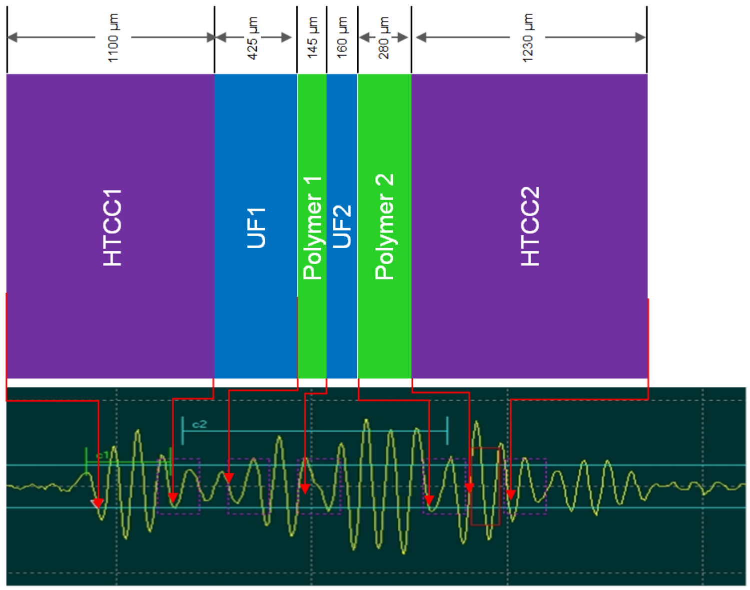

Figure 6. Echo pulse-train of the multilayer sample impinged with 100MHz acoustic wave packet. The arrows indicate the timed locations of each interface. Waveform sampling rate is 4GHz, and time resolution is 0.5ns. Also note that HTCC and Polymers are multilayer stacked-ups.

At optimum transducer frequency and focus depth, the echo waveform composition can be understood by measuring arrival time provided that approximate sound speed and thickness of each material is known. In the SAT system we utilized in this study, the sound speed of most electronic materials are readily available, and the time of flight can be measured using cursors with a resolution of 0.5ns on time axis. Therefore, we focused the beam to the middle of the packages and opened 6 echo gates to image all layer interfaces simultaneously. Although the flaws can be detected by using one sample only, we present images of 3 samples together to make the discussion easier to visualize.

Figures 7(a), (b), (c),(d),(e), and (f) show 6 SAT images acquired by opening six different gates responsible for each layer interface to be inspected for 3 packages. The package at the middle is known to be an internally good unit while there is a misplaced surface mount device on it. The unit at left side has known electrical failure at left bottom area, and the unit at right side has electrical failure with no further information available.

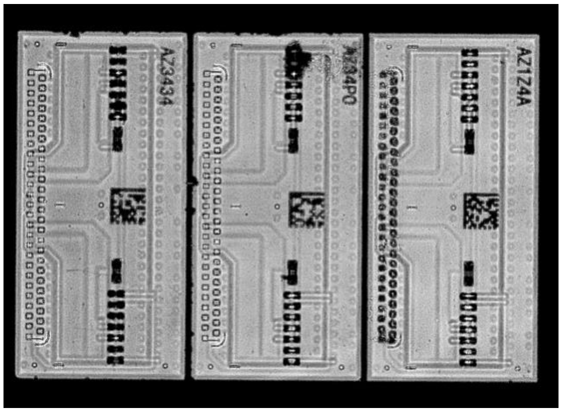

Figure 7(a). C-scan image from Gate #1 representing bottom layer of HTCC1 at 100MHz probe frequency. All 3 units show very similar images, except the shadow of misplaced surface mount condenser is seen differently at the center unit.

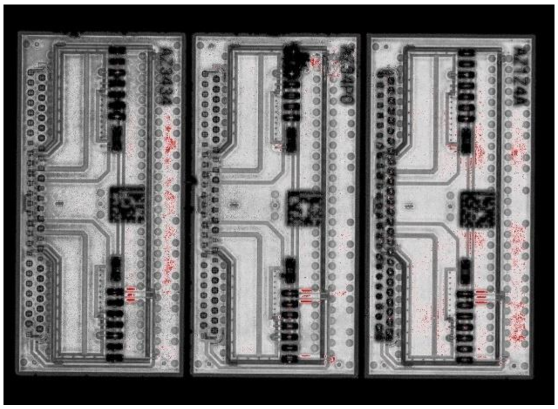

Figure 7(b). C-scan image from Gate #2, interface of HTCC1 top of UF1 at 100MHz probe frequency. All 3 units show very similar images. The inspection algorithm is set so that red color paint will highlight whenever a delamination of void is detected.

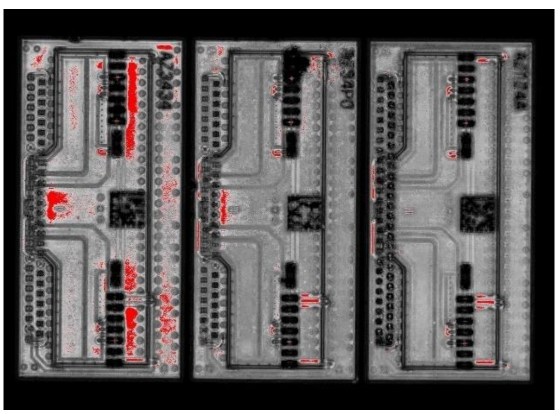

Figure 7(c). C-scan image from Gate #3, UF1 and polymer 1 Interface at 100MHz probe frequency. The inspection algorithm is set so that red color paint will highlight whenever a delamination or void is detected. Serious flaws can be seen in the left middle of the left most unit possibly from UF1.

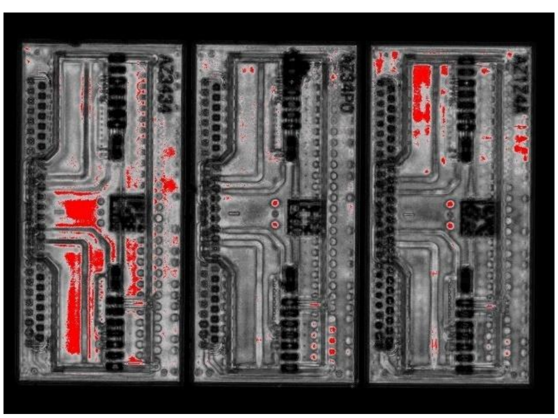

Figure 7(d). C-scan image from Gate #4, top of UF2 at 100MHz probe frequency. Both Left and Right units show significant delamination or less dense material regions as highlighted by red color. UF1 and some part of UF2 have flaws.

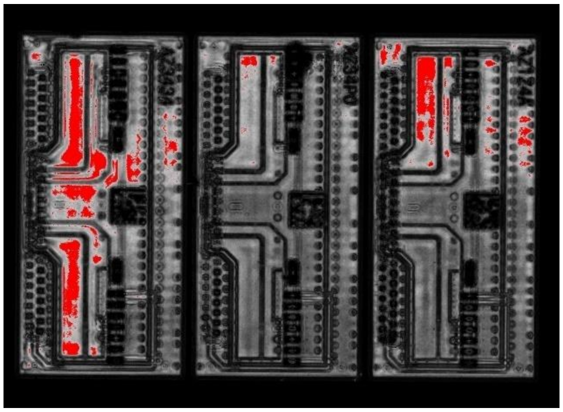

Figure 7(e). C-scan image from Gate #5, UF2, organics interfaces at 100MHz probe frequency. Both Left and Right units show significant delamination or less material regions.

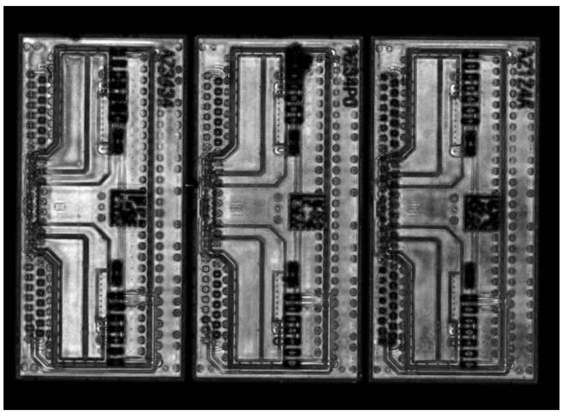

Figure 7(f). C-scan image from Gate #6, top of HTCC2 at 100MHz probe frequency.

While acquiring the images of every echo in a gate, the intensity level is simultaneously analyzed by an inspection algorithm to highlight red color over any area with an abnormal increment of echo intensity caused by delamination or marginally low material density. As expected, the good part at the center exhibits very small red area for any layers imaged by the gates numbers 1 through 6. Inspecting the images of left part revealed that middle to bottom area at the lower level underfill UF2 has serious delamination, the finding generally agreed with the open pin area as indicated by independent electrical test report.

Recalling the images on Figures (2) to (5), the right side sample is the one we emphasize in this capability study with electrical fails at unknown area. The SAT inspection of this sample indicates that while upper underfill layer is free from flaws, top left corner of lower underfill layer (UF2) has delamination as shown in Figure 7(d). This flaw area is also appeared in Figure 7(e) at the attachment to the surface of HTCC2. All these flaw locations can also be confirmed by taking multiple synchronized A-scan waveforms of interested locations on the samples and by comparing their peak heights.

Cross Sectional Confirmation

We have selected the left most package of Figure 7 which showed delamination flaws from the top to the lower polymer layer to cross-section if we can confirm the flaws highlighted by red color. As expected the upper layer flaws at the center of the device are clearly observed under 150 x optical microscope as shown in Figure 8.

The delamination at lower level are somewhat difficult to distinguish optically at 150 x, and required higher magnification and image comparison. We carefully have inspected lower level joints at higher magnification up to 500 x as well as by comparing with images of similar location of a different part. We noticed stronger contrasts at the boundary indicating a signature of thin delamination at the stack-up joint.

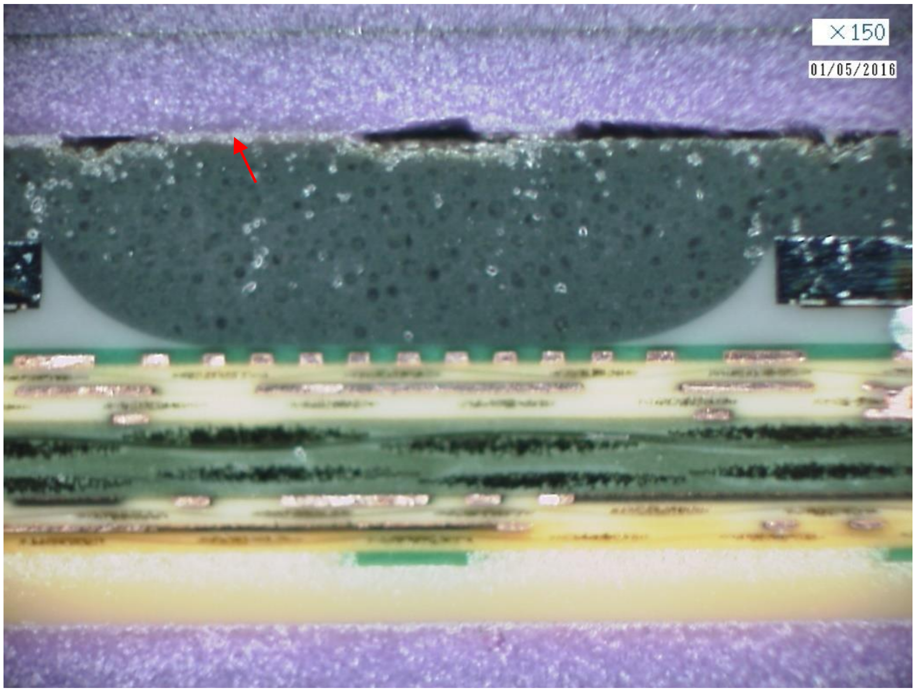

Figure 8. Cross section image of center region with 150x optical microscope

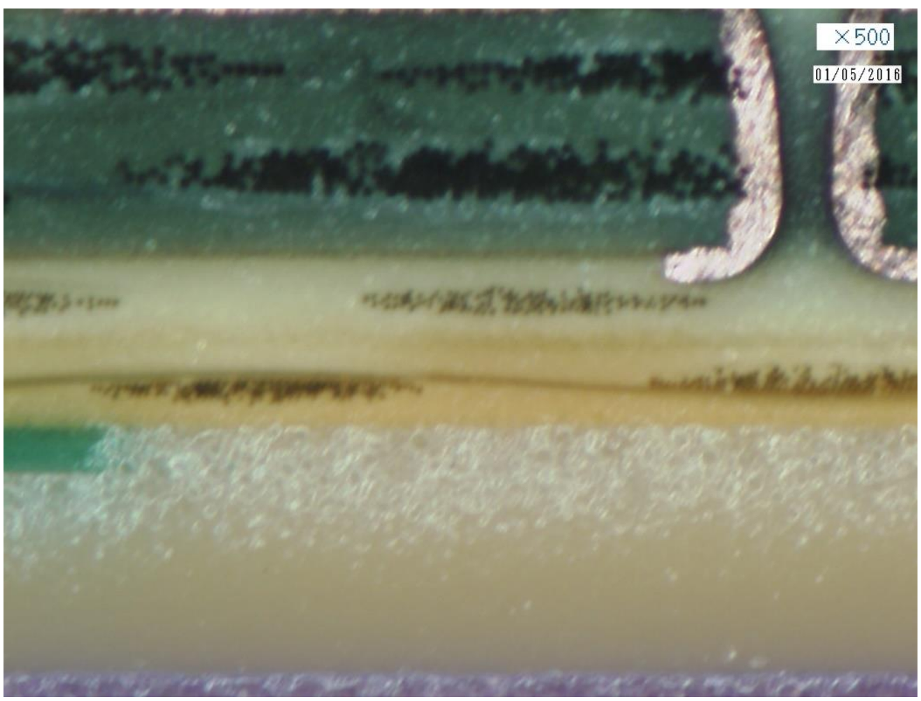

Figure 9. Cross section image of center region with 500x optical microscope, the lower level delaminations are somewhat difficult to distinguish by optical cross sections.

Conclusions

This work has demonstrated that SAT images from a multilayer stack of ceramics-organics-ceramics structure with embedded devices can be separated to individual layers to characterize if flaws are included in the acoustically deep layers. The SAT findings are confirmed by cross sectioning a selected sample. To successfully image such samples, the transducer frequencies should be able to be varied at will in certain ranges and the acoustic beam spot should be small while focal length of the probe long is enough for a given sample.

Acknowledgements
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References
1. K. Kitami, M. Takada, O. Kikuchi, and S. Ono, “Development of High Resolution Scanning Acoustic Tomograph for Advanced LSI Packages, “Proceedings of 20th IEEE International Symposium on the Physical and Failure Analysis of Integrated Circuits, 2013, pp 530-533.
2. K. Kitami, M. Murai, N. Sugaya, O. Kikuchi, and S. Ono, “New Technique for Acquiring Dead Pixel Free and Fine Inspection Image of Advanced LSI Package with Rough Surface using Scanning Acoustic Tomograph, “Proceedings of 21stIEEE International Symposium on the Physical and Failure Analysis of Integrated Circuits, 2014, pp 530-533.
3. Z. Feng, D. Geiger, W. Liu, A. Mohammed, M. Kurwa, and G. Tint, “Characterization of Solder Defectsin Package-on-Packages with AXI Systems for Inspection Quality Improvements,” Proceedings of IPC APEX, San Diego, CA, 2015.
4. D. Geiger, Z. Feng, J. Nguyen, W. Liu, A. Mohammed, M. Kurwa, G. Xu, L.Su, and G. Tint, “Optimization of X-Ray Inspection for Solder Charged Connectors,” Proceedings of SMTAI, Chicago, IL, 2015.
5. G. Tint, “Transducer Properties for High Definition SAT Imaging of Semiconductor Packages,” Chip Scale Review Magazine, June 2007.

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Flex International; Hitachi Power Solutions[#]; HDI Solutions[&]

Agenda

- Introduction
- Experiment
  - SAT Preview
  - SAT Layer by Layer View
  - Confirmation by Cross-Sectioning
- Conclusions

Introduction

Motivation for this project

multi-layer device structure difficult to inspect nondestructively

Highlights of SAT Machine

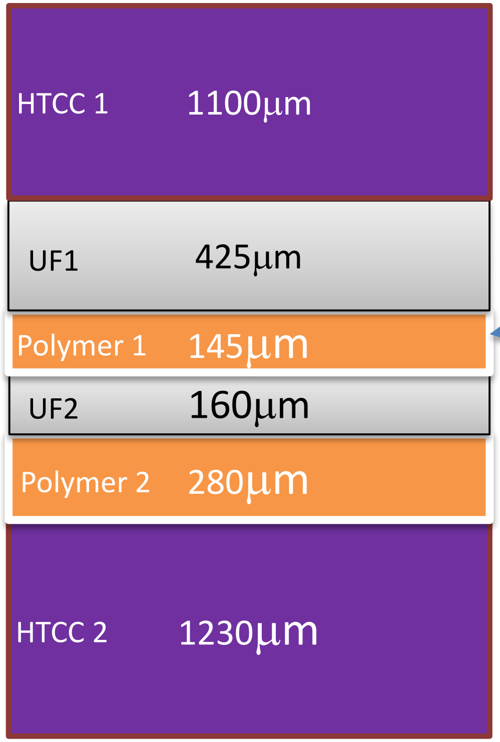
high resolution/ excellent signal-to-noise ratio

Optimized Method

with new technology, can we image flaws in multi-layer embedded packages?

Illustration of Sample Structure

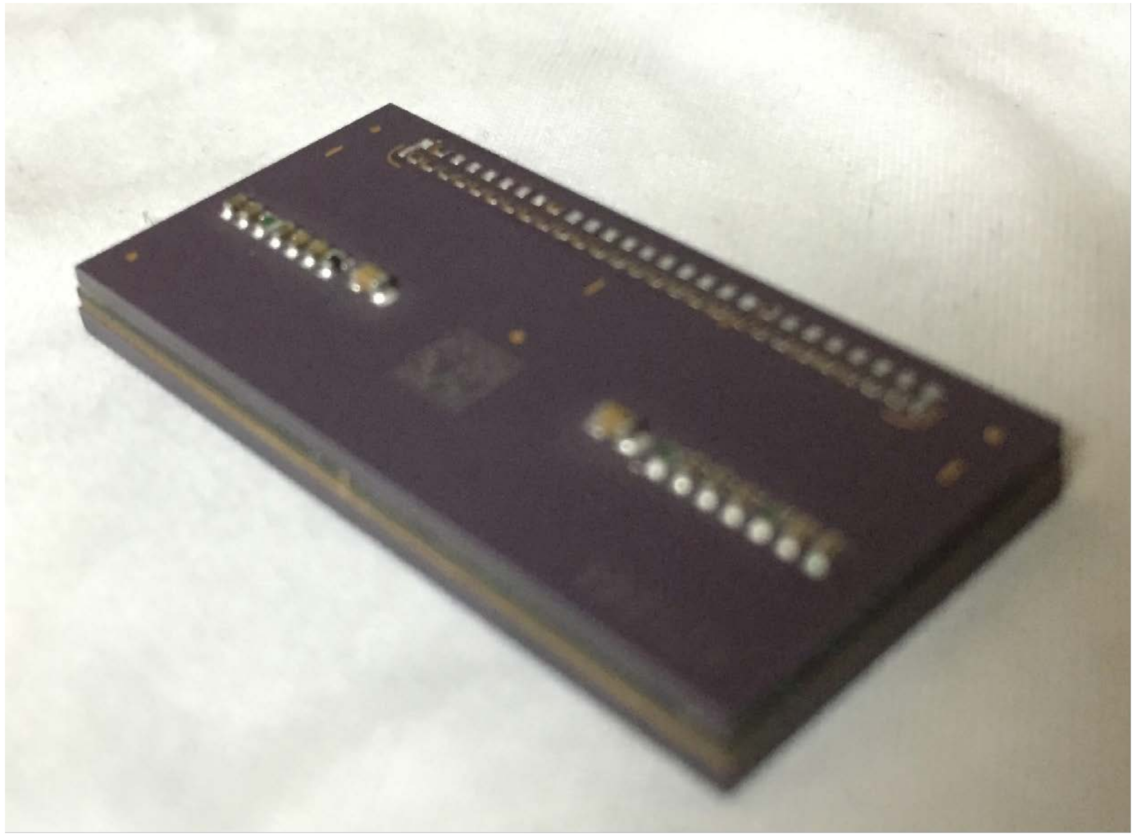
- Side View : Layer Thickness in micron



Polymer substrates are mounted with a couple of silicon devices

Sample Structure

- Actual sample with SMT components on top



Objective:

To characterize the voids patterns at the lower underfill layer

Nondestructive Inspection Strategy

- X-ray CT Inspection
- Ultrasound Inspection (SAT)
- Objectives
    1. To identify each of the layers by CT and SAT
    2. To inspect flaws in the individual layers/Interfaces
    3. Confirm the nondestructive inspection results by cross-sectioning

CT Imaging layers top to bottom

We briefly ran this sample with X-ray 3d-CT System and no obvious metal flaws were detected.

For CT inspection, detection of delamination flaws are difficult to detect, however it is an excellent tool for detecting metal/solder voids

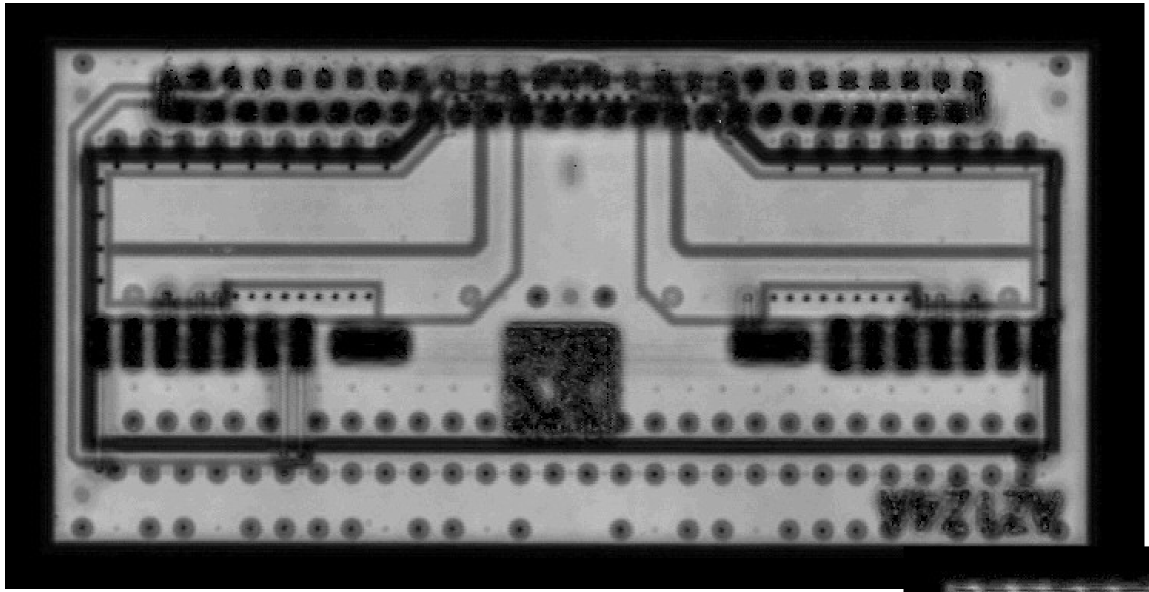
CT- layer by layer movie is available for this sample.

SAT Inspection

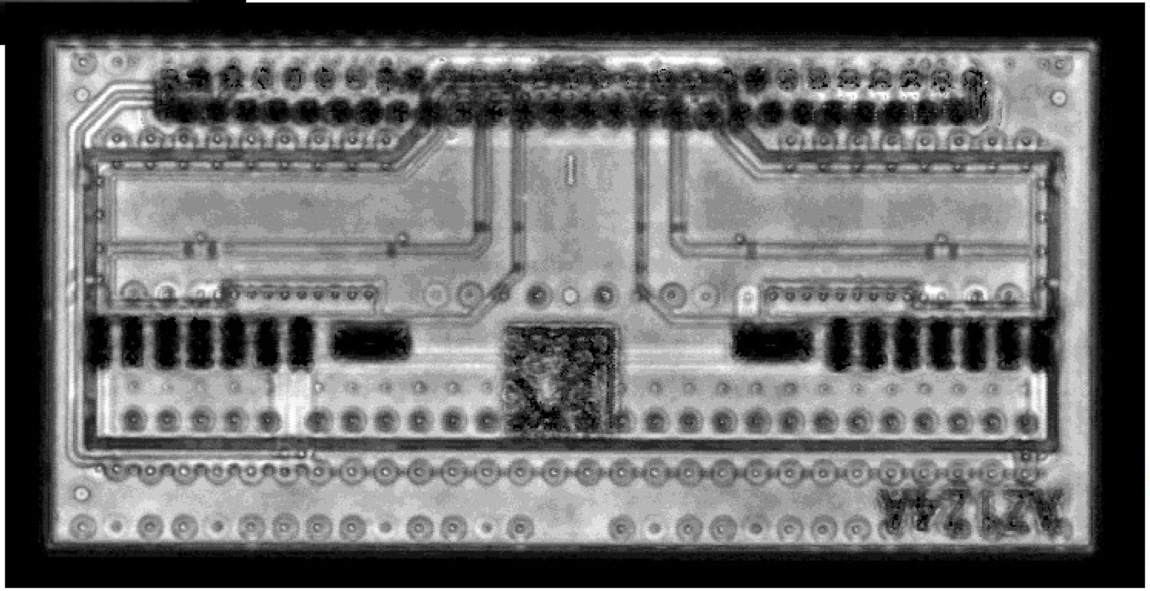
- Step 1
    - Identify inner Layers with known patterns
- Step 2
    - Check general layer integrity with Through Transmission Scan
- Step 3
    - Use Reflection for better detectability and resolution
    - Increase transducer frequency for better layer separation
    - Quantify the flaw level

SAT System with High Resolution Unit

SAT Reflection Images with 50 MHz Probe

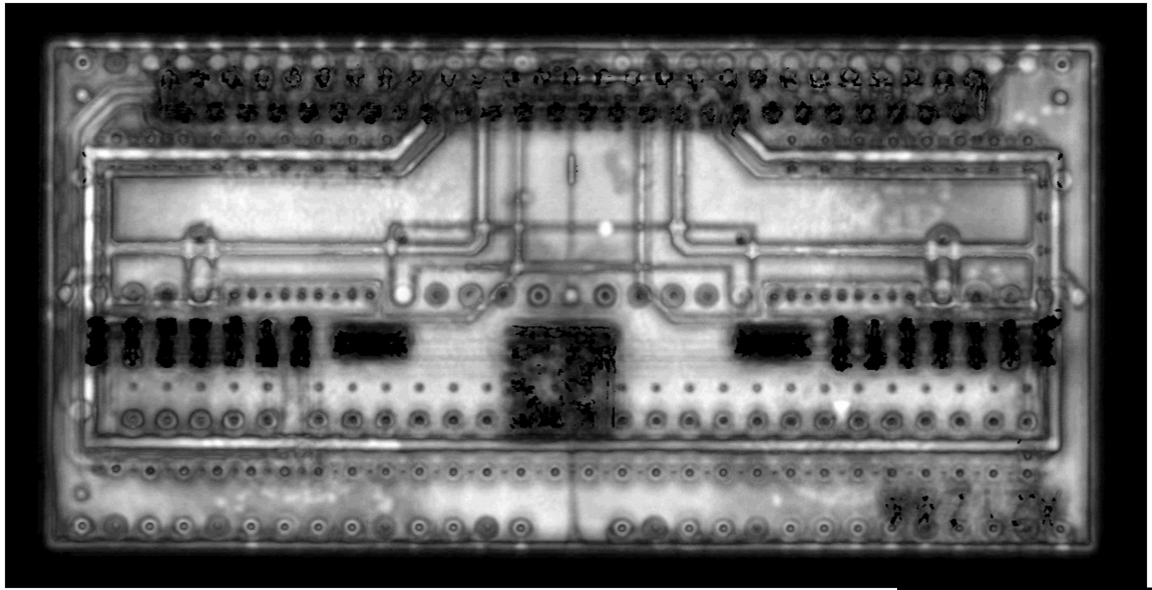


Upper Underfill Layer (Focused)

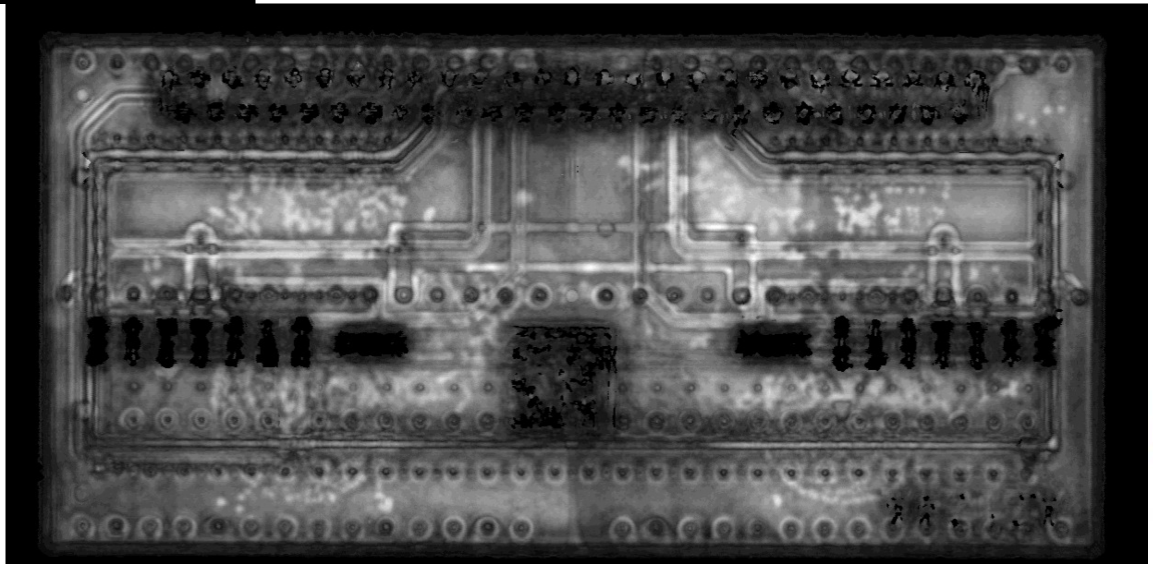


Lower Underfill Layer
(Focused@ Upper UF Layer)

SAT Reflection Images for 50 MHz

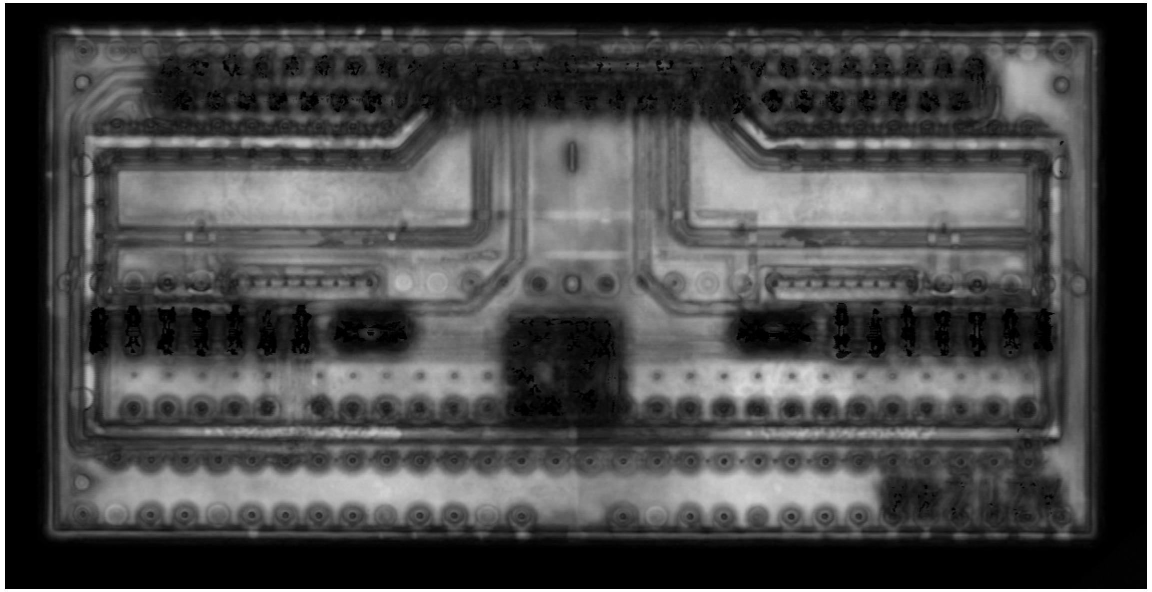


Upper Underfill Layer
(Focused@ Lower UF Layer)

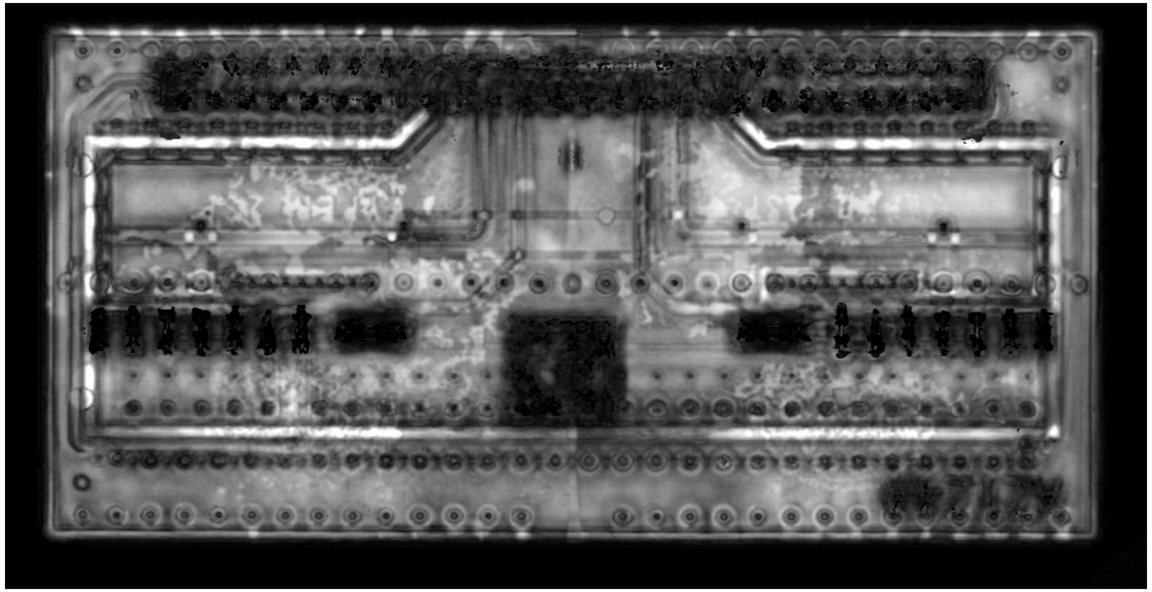


Lower Underfill Layer (Focused)

SAT Reflection Images for 100 MHz



Upper Underfill Layer
(Focused@ Lower UF Layer)



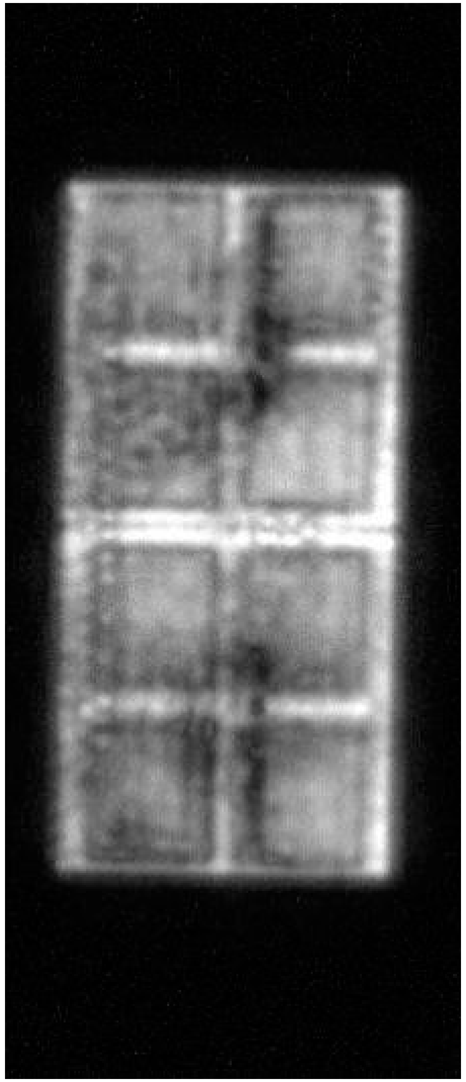
Lower Underfill Layer (Focused)

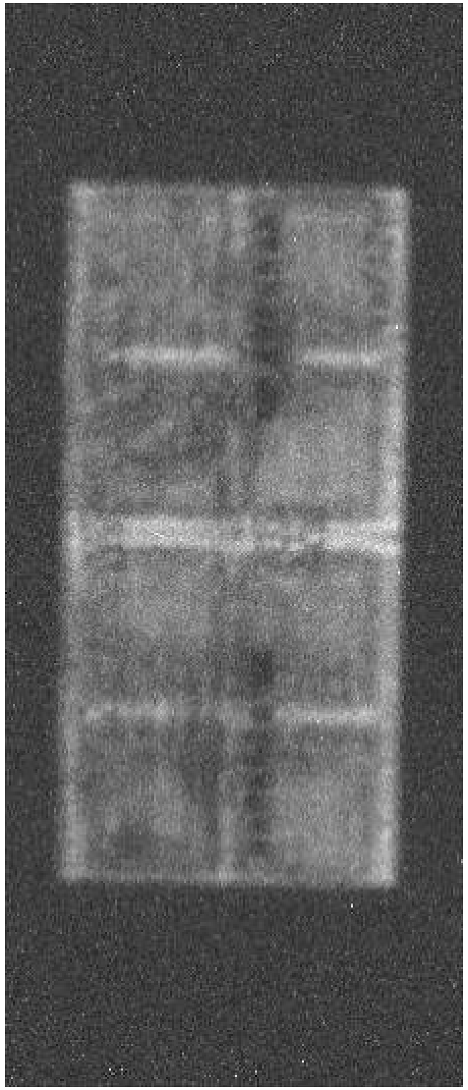
Conclusion 1

- The interfaces of associated underfill 1 and underfill 2 can be distinguished at probe frequencies from 50MHz to 100MHz

SAT Transmission Images : Single Unit

15MHz non-Focused

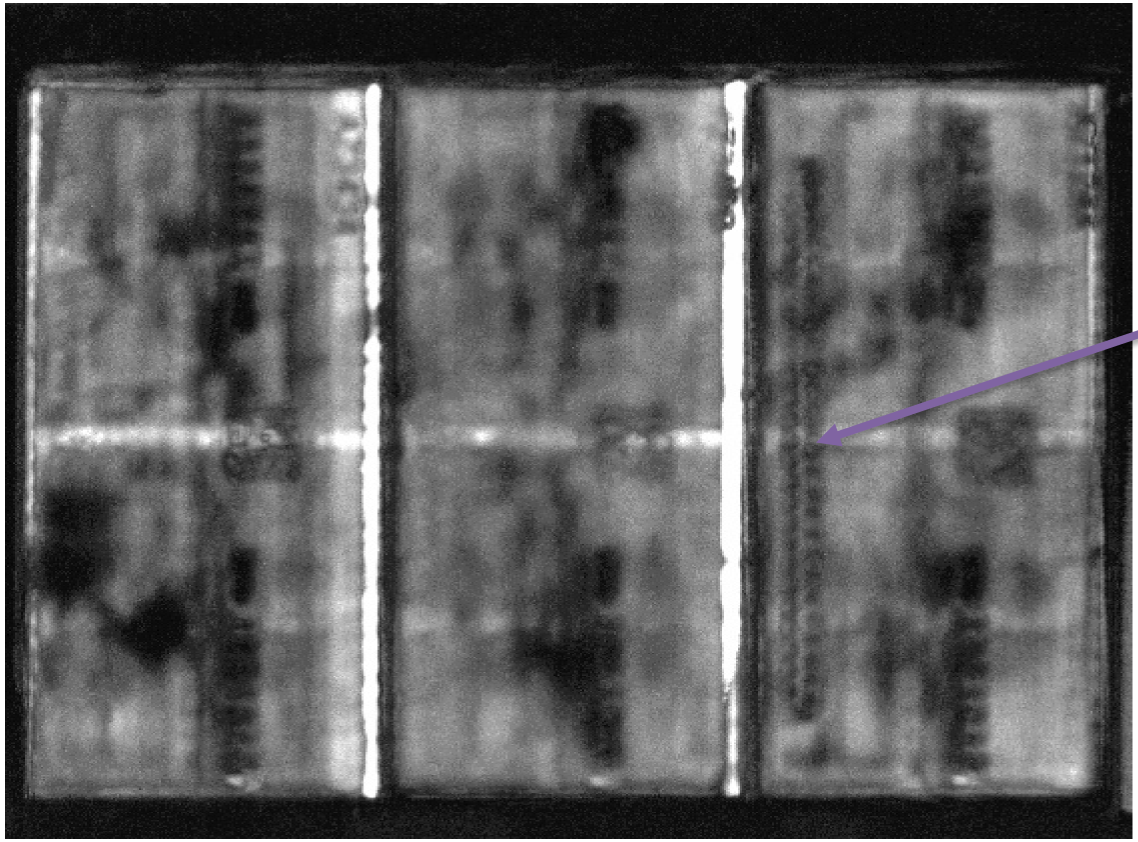




25MHz Non-Focused

SAT Transmission Images : 3 Units

15MHz non-focused



Desoldered joints

Electrical Screening Result | Bad Unit | Good Unit | Bad Unit

Comments on Transmission Images

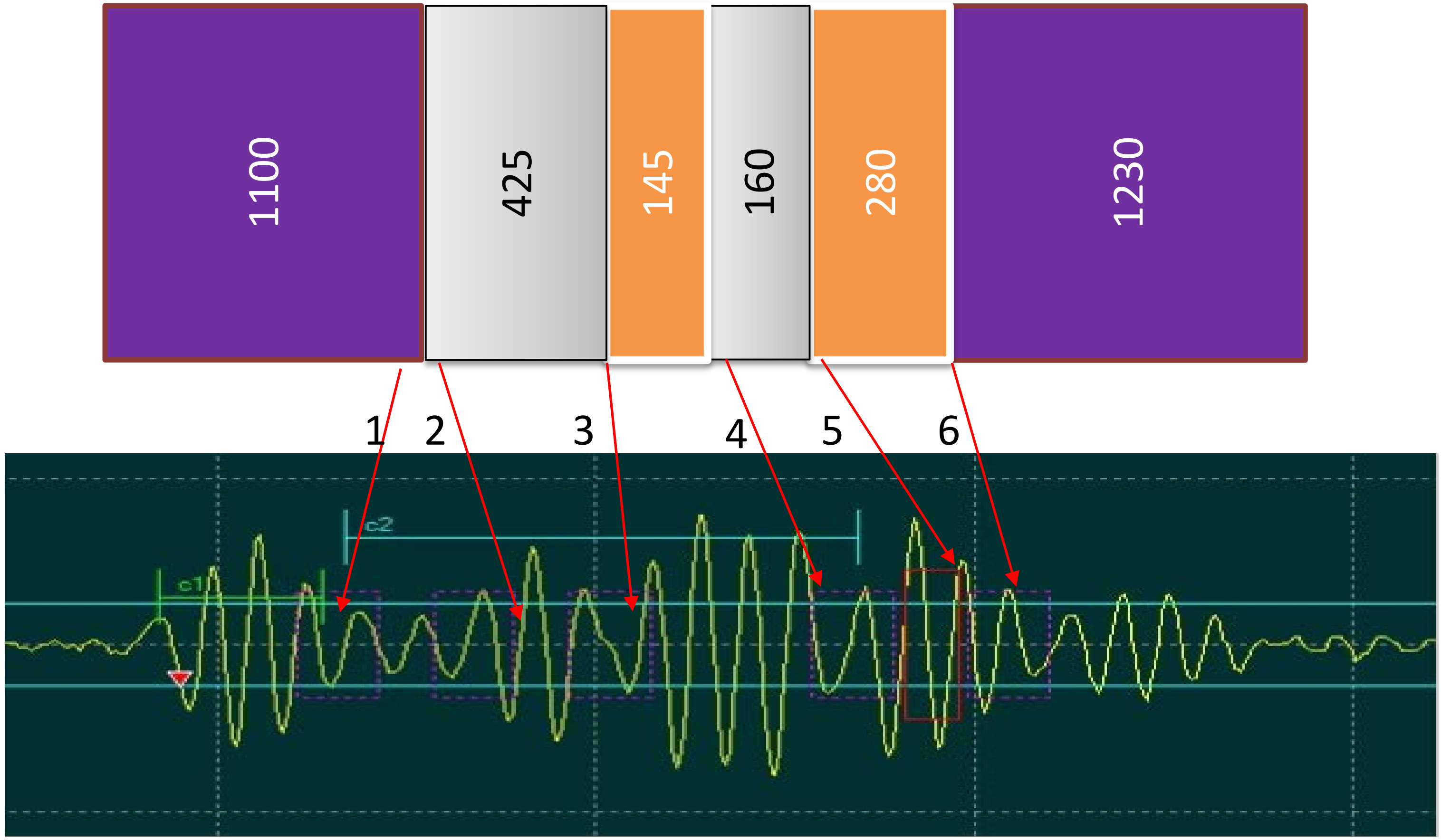
- Quick Check
- Difficult to pinpoint which layer is bad
- How Black is Bad?
- Is black spot really responsible for Underfill flaw?

- We have more questions

Reflection Inspection for Layer Identification

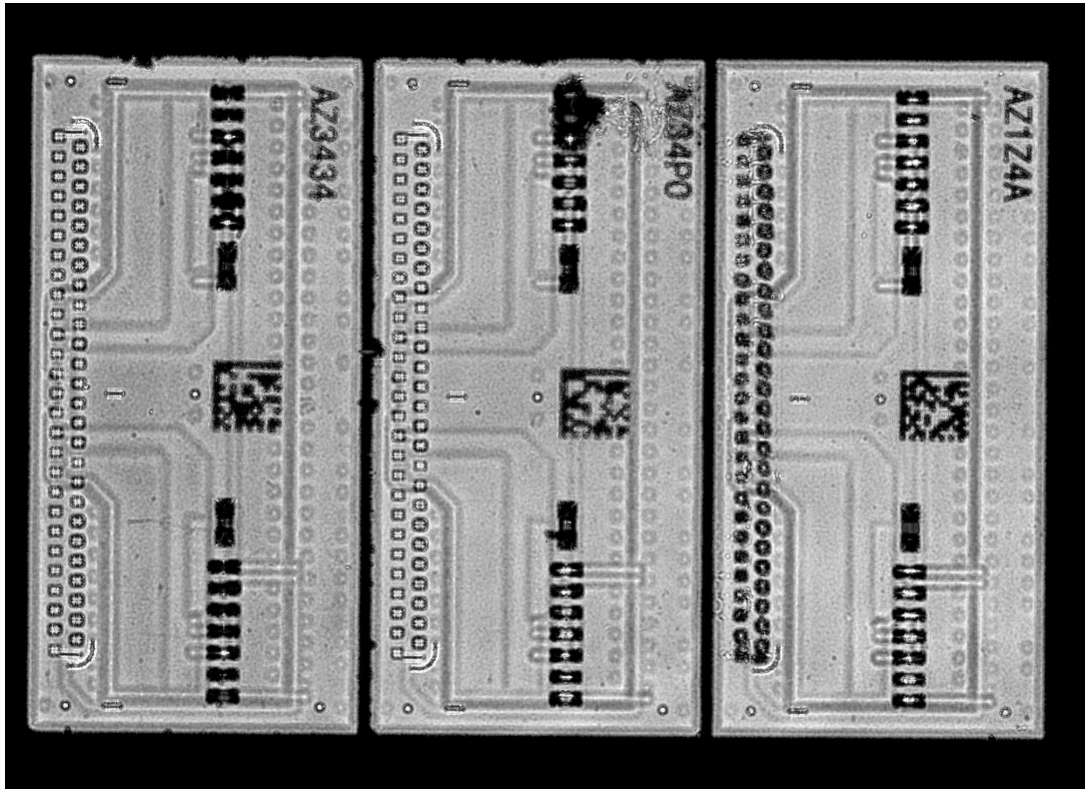
- In the reflection mode, echoes reflected from layers and interfaces can be identified by resolving their arrival time, which is also dependent on acoustic impedance or speed of sound in that material.
- In this sample, our region of interest is underfill material stack clapped with high sound impedance materials, HTCC.
- Transducers with frequencies of 15MHz to 120MHz are used in this study.
- Lower frequency sound penetrate deeper, while higher frequency waves offer higher time resolution.
- From this sample, frequency range 90-100MHz is optimum: layers well separated and minimal distortions originated from constructive/destructive superposition.

Reflection: Analytics of Waveforms

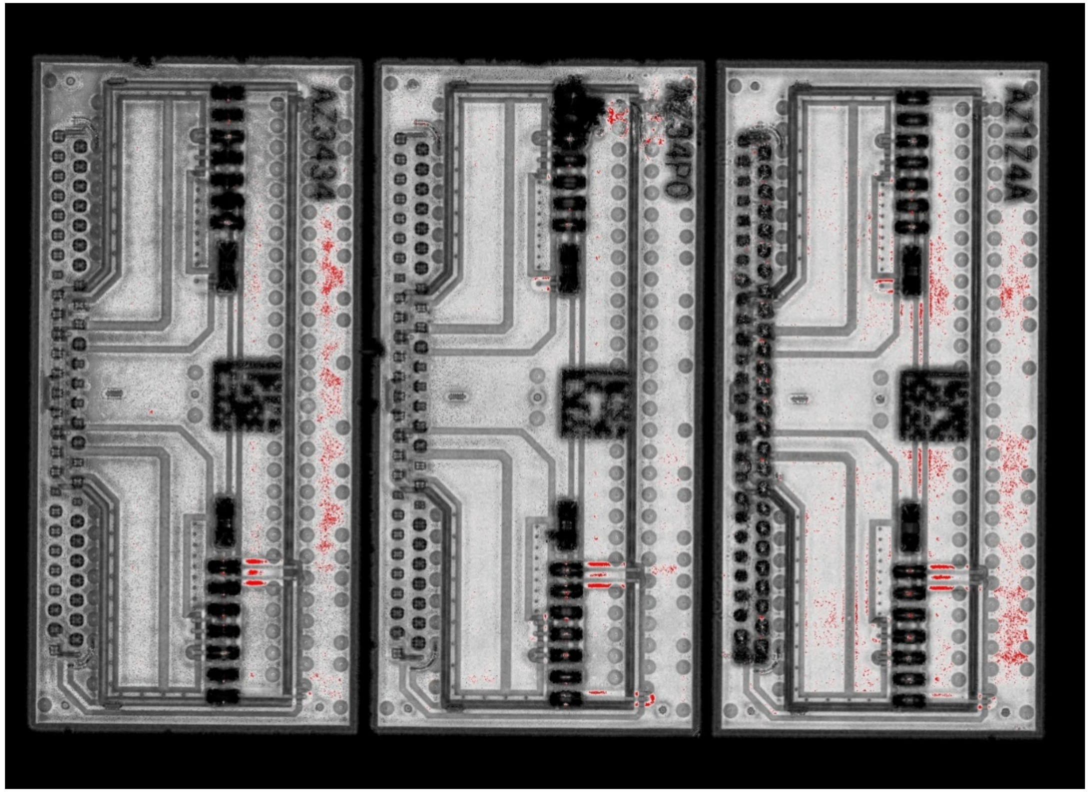


100 MHz Reflection

Gate 1



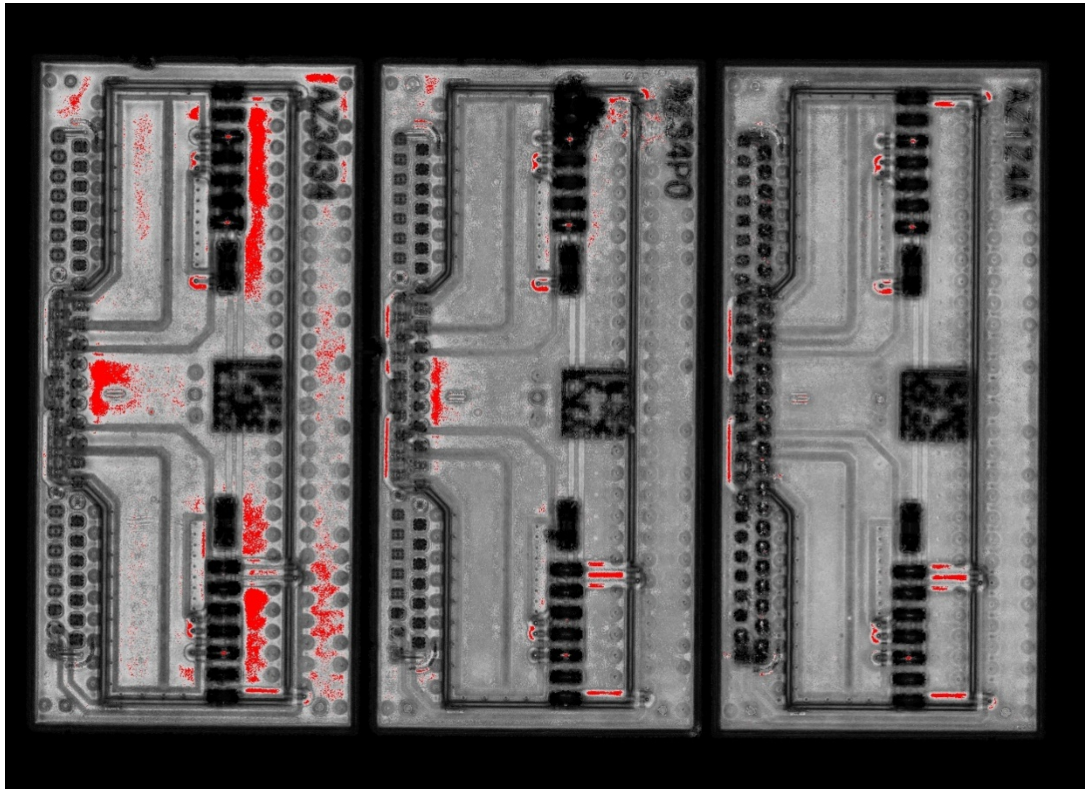
Gate 2



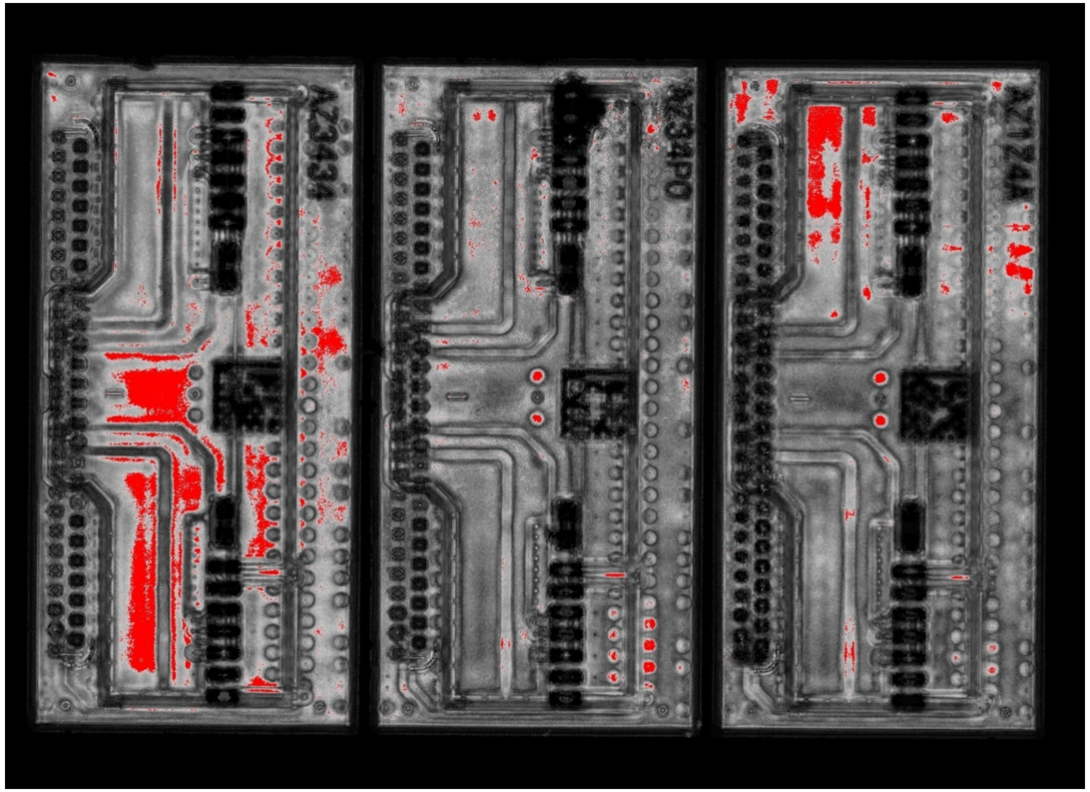
HTCC1 bottom layer

100 MHz Reflection

Gate 3



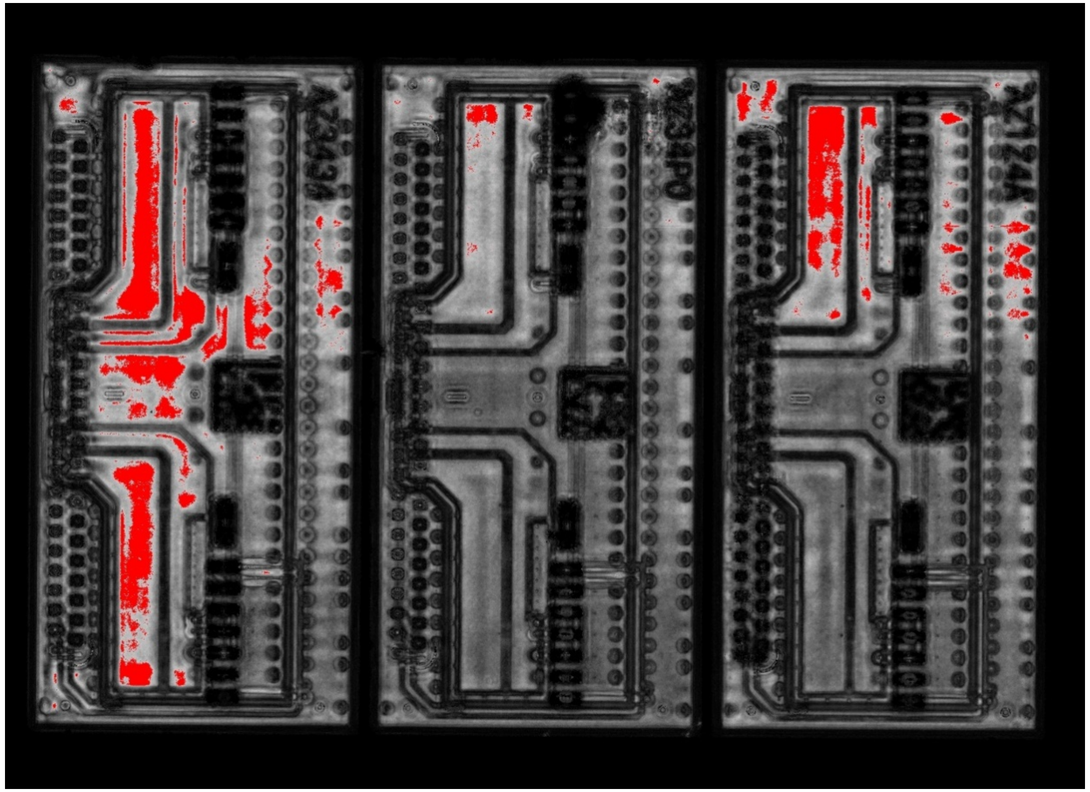
Gate 4



UF1 layer flaw regions are highlighted by red color

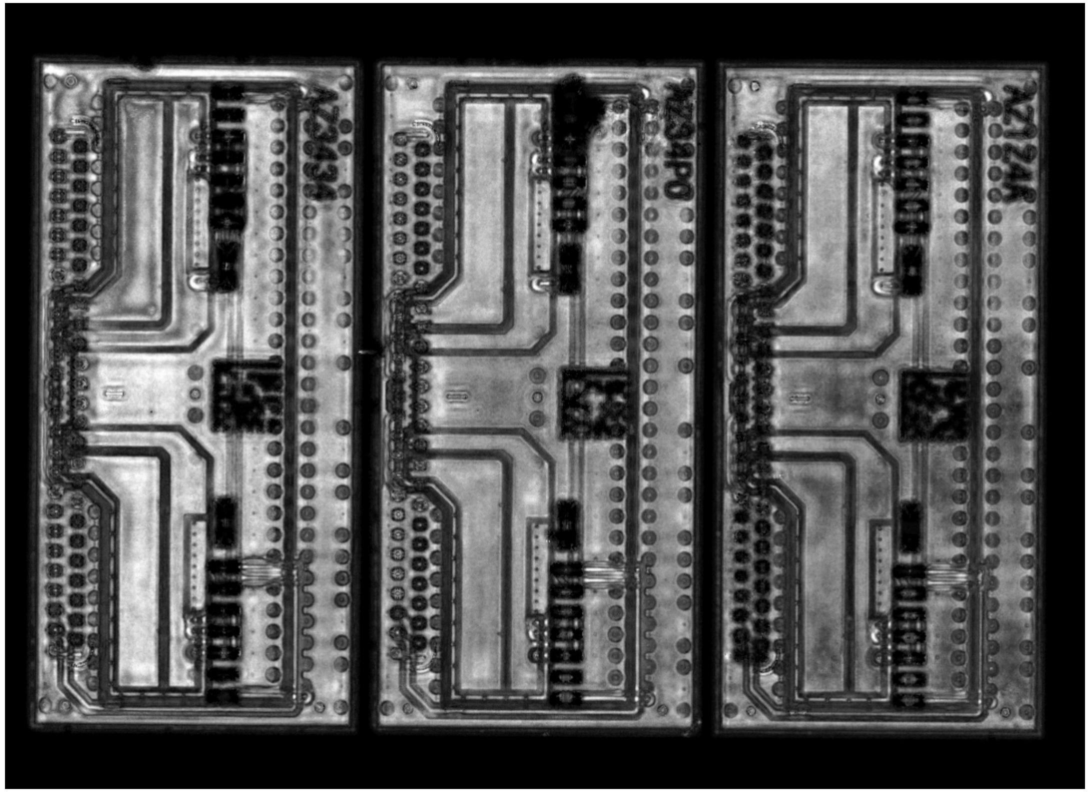
100 MHz Reflection

Gate 5



UF2 Layer

Gate 6



HTCC2 Layer

Standard Analysis Tools

- Level: Echo level analysis indicated above
- Depth: Time of Flight Analysis
- Void Area based Judgement : for automated inspection
- Largest Void Size based Judgement
- A- Scan : Spectroscopic Waveform Analysis

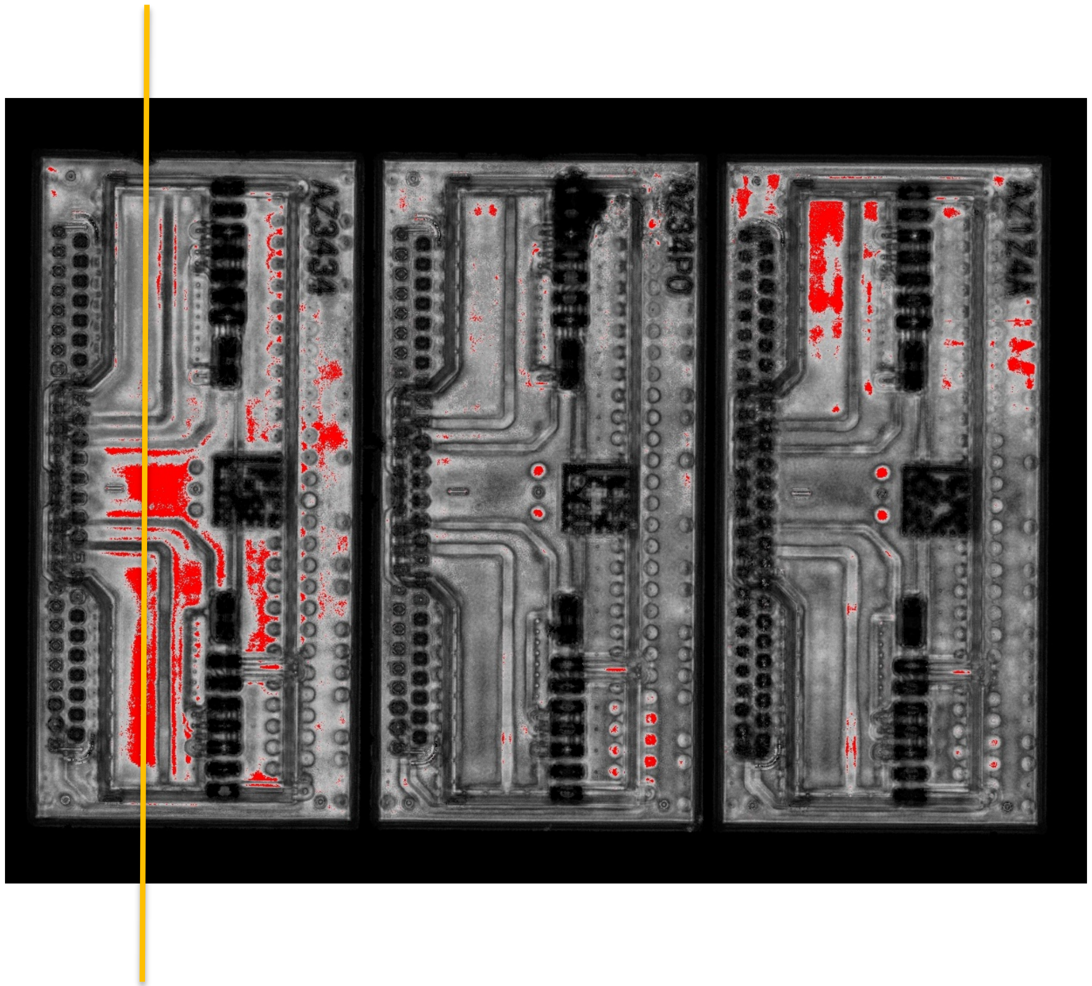
Results and Discussion

- CT
  - Flaws of these kinds in softer materials are hard to see with CT Technology
- SAT
  - Through transmission images are not explicit as usual when you have so many layers stacked up
  - Reflection C-SAM Image acquired with highest possible frequency will have good layer separation.

Cross-Sectional Confirmation

Gate 4 : middle gate

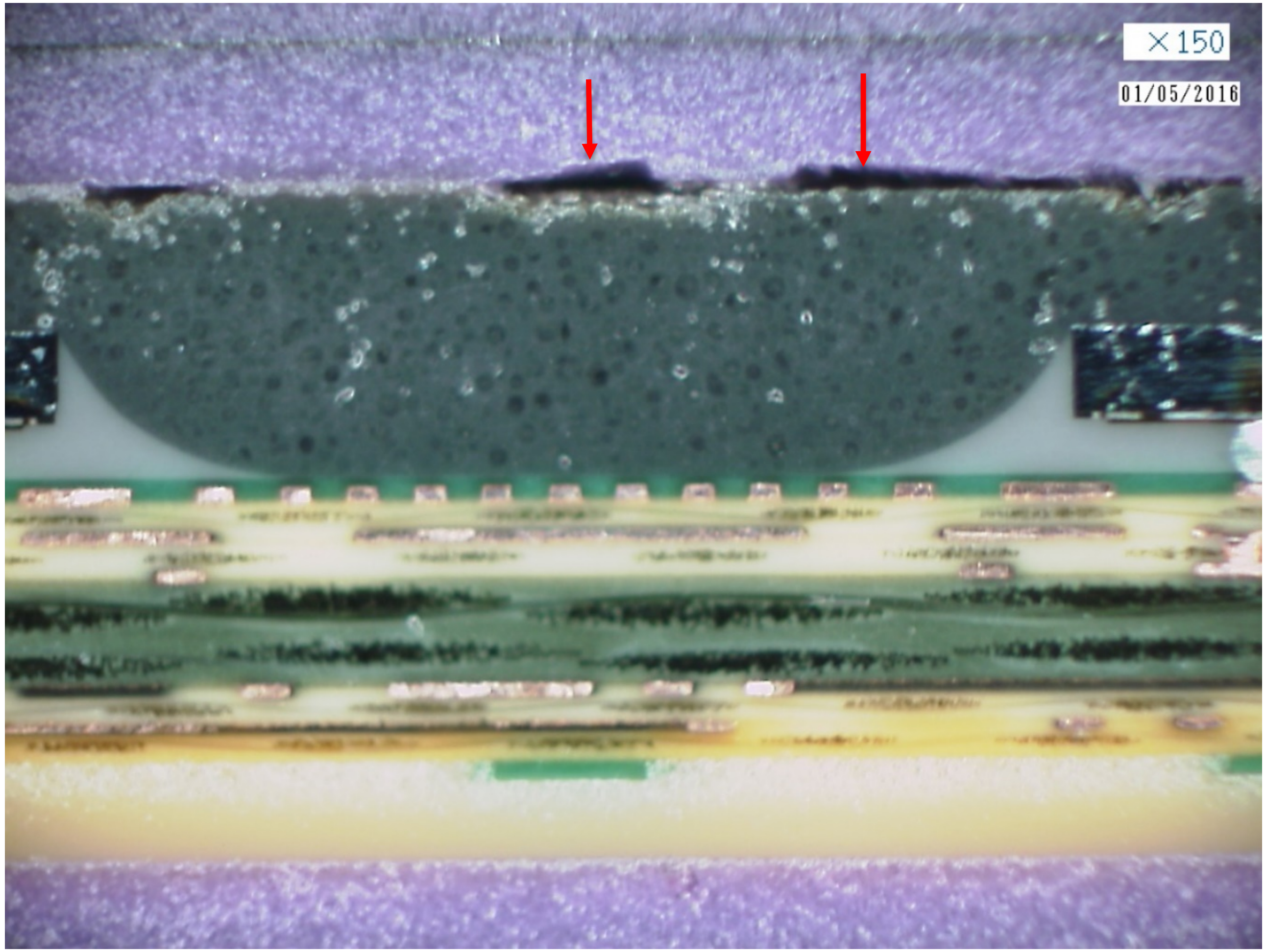
Expected flaws Locations



Plane for Cross section

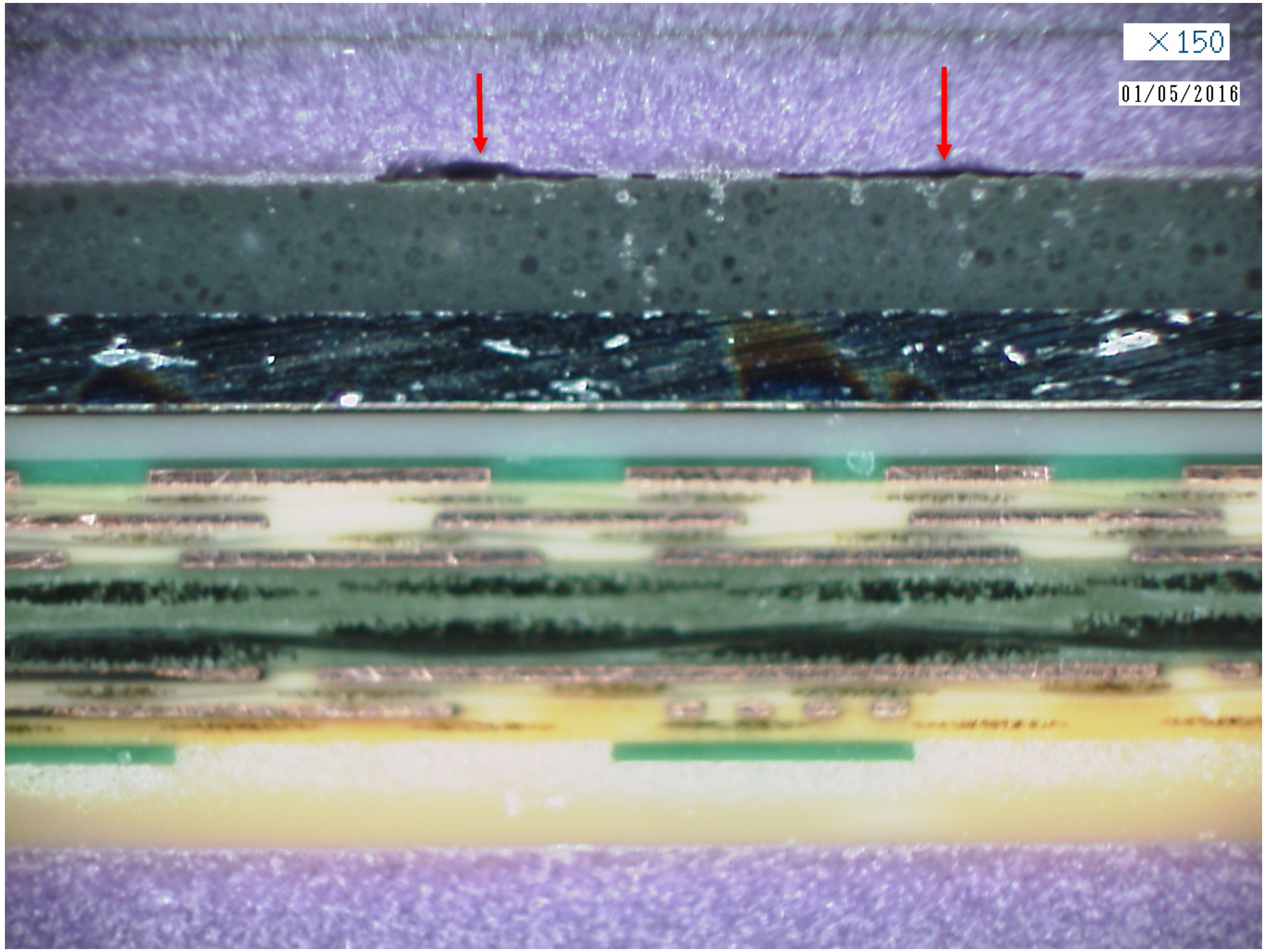
Cross-Sectional Confirmation

Middle part



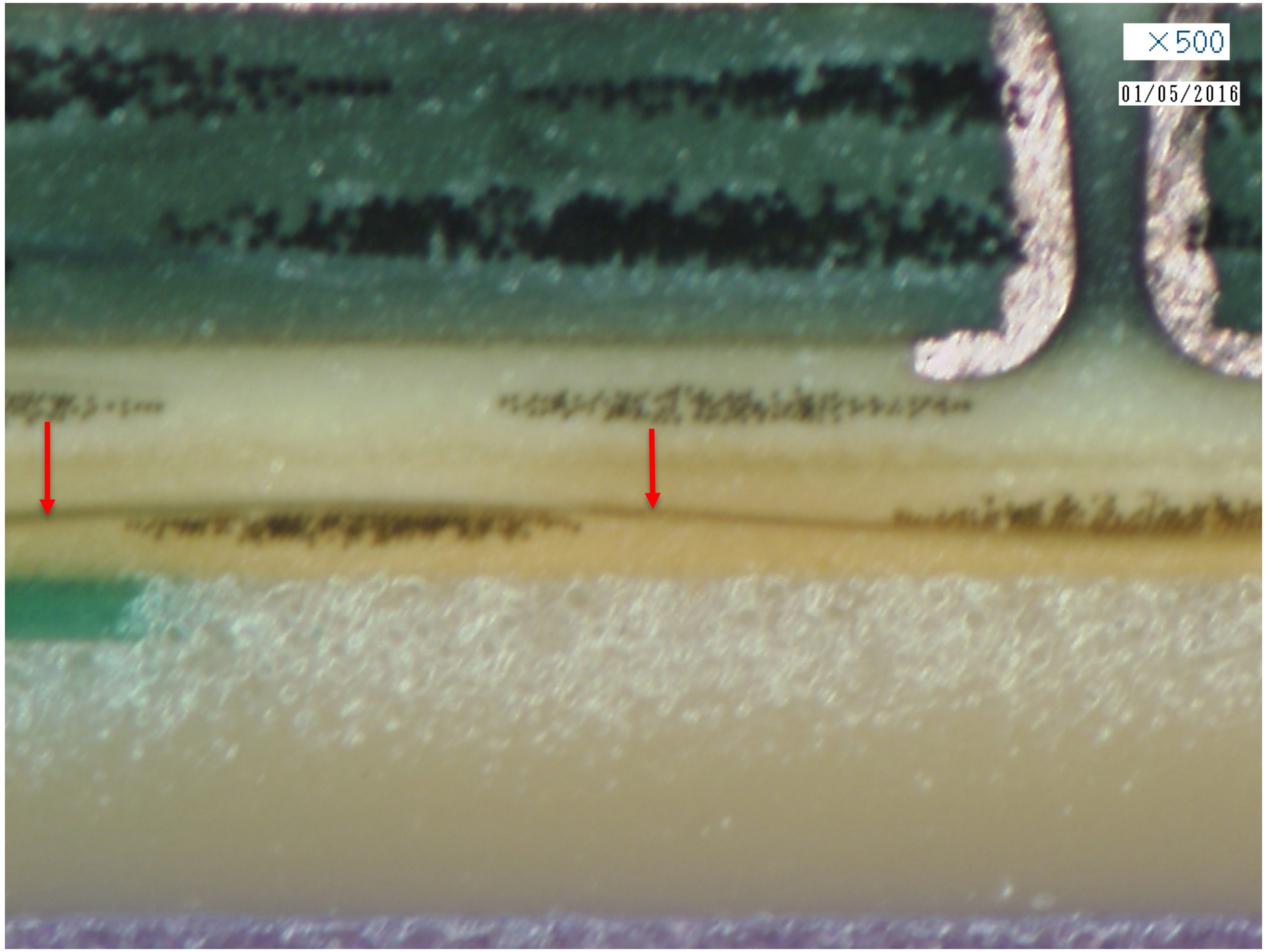
Cross-Sectional Confirmation

Lower part



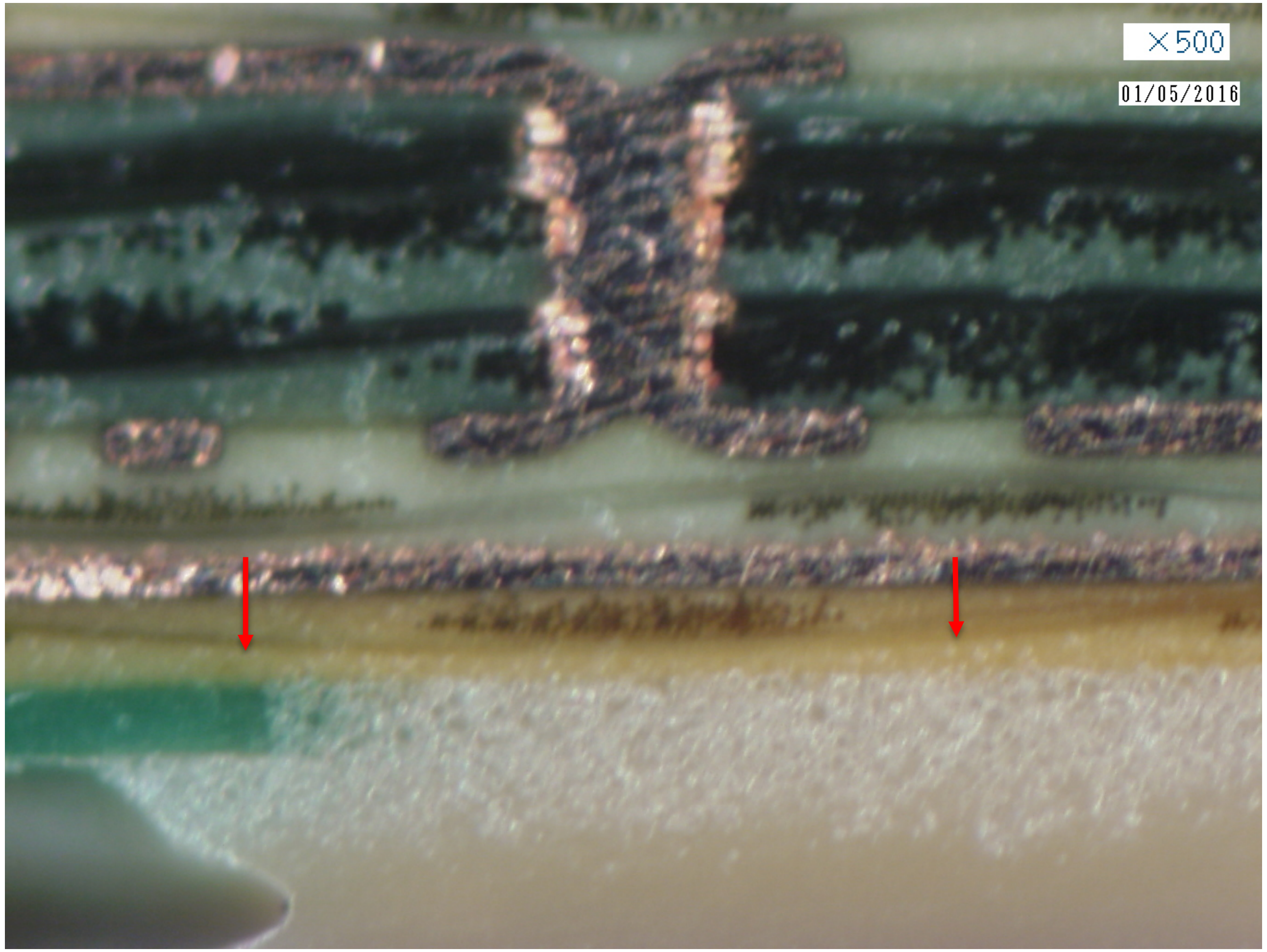
Cross-Sectional Confirmation

Deeper layer/ difficult to distinguish optically



Cross-Sectional Confirmation

Deeper layer/ good joint



Conclusions

- SAT can easily catch UF1 level flaws
- SAT can also catch 2nd Level Underfill Voids in complicated Ceramics/Organic flip-chip embedded structure
- Flaws in Underfill layers are seen with probe frequencies (90-100MHz)
- Cross-Sectioning of one sample confirmed the SAT findings

Thank you so much for attending!

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