Addressing Failure Analysis Challenges in Advanced Packages and MEMS using a novel Phase and Darkfield X-ray Imaging System

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Abstract

Currently gaps in non-destructive 2D and 3D imaging in PFA for advanced packages and MEMS exist due to lack of resolution to resolve sub-micron defects and the lack of contrast to image defects within the low Z materials. These low Z defects in advanced packages include sidewall delamination between Si die and underfill, bulk cracks in the underfill, in organic substrates, Redistribution Layer, RDL; Si die cracks; voids within the underfill and in the epoxy. Similarly, failure modes in MEMS are often within low Z materials, such as Si and polymers. Many of these are a result of mechanical shock resulting in cracks in structures, packaging fractures, die adhesion issues or particles movements into critical locations. Most of these categories of defects cannot be detected non-destructively by existing techniques such as C-SAM or microCT (micro x-ray computed tomography) and XRM (X-ray microscope). We describe a novel lab-based X-ray Phase contrast and Dark-field/ Scattering Contrast system with the potential to resolve these types of defects. This novel X-ray microscopy has spatial resolution of 0.5 um in absorption contrast and with the added capability of Talbot interferometry to resolve failure issues which are related to defects within organic and low Z components.

Introduction

Talbot-Lau X-ray Interferometry for Phase Contrast and Darkfield Imaging.

Absorption contrast is the conventional mechanism upon which current x-ray imaging techniques (Realtime 2D X-ray and 3D X-rays/microCTs/XRM) are based upon. However, there are several failure mechanisms in advanced packages and MEMs devices where there are currently no good non-destructive solutions. Many of these issues are related to insufficient resolution and the lack of contrast to visualize defects in the low Z or organic materials.

X-ray imaging of interfaces between organic components can be successfully done using phase contrast imaging. However, most of these phase imaging requires a synchrotron X-ray source that has a high spatial coherence [1,2]. One of these phase contrast techniques is the Talbot-Lau interferometry, which uses a set of three gratings in the path of the x-ray beam.[3]

Talbot-Lau interferometry provides three x-ray radiographs simultaneously: absorption contrast, phase contrast, and scattering (darkfield) contrast. This multi imaging technique is very promising for non destructive inspection of electronic components because in addition to the absorption contrast and phase contrast imaging, one can also observe ultra small angle X-ray scattering dark field effects.

X-ray dark-field imaging has received much attention for its potential applications in medical imaging [4,5,6] and non-destructive material testing [7,8]. As the dark field image contrast is formed through the mechanism of small-angle scattering, it provides complementary and otherwise inaccessible structural information about the specimen at the micrometer and sub-micrometer length scale, which is significantly below the resolution of conventional X-ray imaging system [9, 10]. This is because dark field scattering is related to the variations or inhomogeneity in the electron density within the sample where there are cracks or voids at the sub- and micron-scale.

Talbot-Lau Interferometry holds immense potential to significantly advance the field of X-ray imaging of defects within low Z materials, ranging from biomedical imaging to semiconductor packaging [9] and industrial applications. Of particular significance is the ability of this novel X-ray Imaging technique with phase contrast and darkfield contrast technique to detect certain class of failures in advanced heterogeneous packages or MEMS which currently have no satisfactory nondestructive imaging solutions. These include cracks, voids, porosity and delamination within low Z materials which have very low X-ray absorption contrast such as underfill, molding compound and Si die. These defects may be observed at micron and submicron lengthscale. Other class of failures include defects within low X-ray contrast organic materials located next to highly X-ray absorbing materials such as metal wires, solder balls, copper bumps or vias.

The Talbot interferometry technique has been demonstrated successfully in synchrotrons beamlines with high spatial coherence. While proof of concept with this technique has also been demonstrated in laboratory systems (Fig.1), so far there are limited commercial applications because of the lack of throughput, limited field of view and poor resolution [12] due to limitations of the approach commonly used.

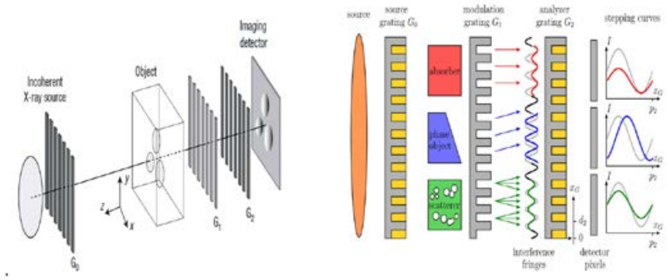

Fig. 1. Grating-based Talbot-Lau interferometry uses three gratings [1]. The source grating (G0) and modulation grating (G1) create interference fringes that are then sampled by an analyzer grating (G2) placed before the detector. Fringe profiles will change as a result of absorption (red), phase shifts (blue), and scattering (green).

In laboratory setups, the first grating, G0, is a major bottleneck. The G0 grating is not only difficult to fabricate but also limits the field of view (FOV) achievable. It is because for the interferometer to operate at higher energy to penetrate electronic devices, the aspect ratio for this first grating has to be high. See Fig 2.

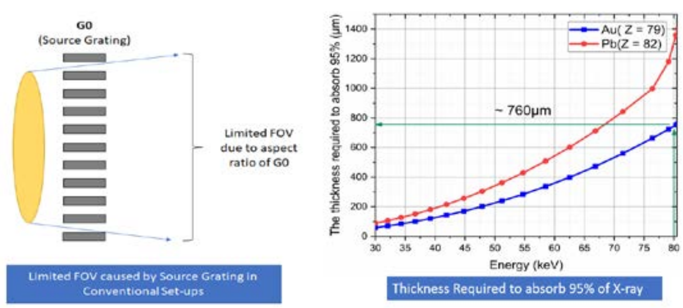

Fig 2: The G0 grating has to be made of heavy elements such as Au or Pb in order to block at least 95% of the x-ray to create the Talbot effect. The graph on the right is a plot of the thickness of different metals required to absorb 95% of x-rays vs X-ray energy.

From Figure 2 it can be seen that the aspect ratio of G0 grating will be high. From the graph on the right, the thickness of Au required to make the grating should be at least 760 um when X-ray tube is operating at 80 keV. With a grating pitch width of only a few microns, such a high aspect ratio grating is not only be difficult to fabricate with current technology, but will also end up with a very limited field of View (FOV).

To overcome the severe loss of throughput and limited field of view in a laboratory setup, we have designed an innovative patented X-ray source in which microstructures of target materials are embedded in a diamond substrate utilizing the pattern of the G0 grating [12]. See Fig.3

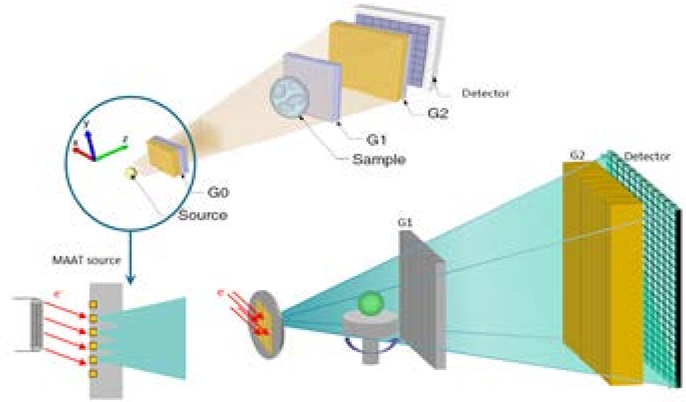

Fig.3 Illustration of the modified Talbot-Lau interferometer where the X-ray source with a MAAT (microstructured array anode target) is used to replace the combination of an extended source and the G0 grating. The MAAT comprises micron sized W metal lines embedded in a diamond substrate. The W metal lines had a width of ~1.3um and the pitch between the lines is 3 microns.

This innovative x-ray source offers many important advantages over the conventional approaches, including more efficient use of source x-rays due to absence of the G0 grating, a larger field of view, and brighter x-ray source due to the use of diamond substrate. Furthermore, the small line width and the pitch of the W lines relaxes the aspect ratio required for G2 grating, which is an absorption grating and requires the grating lines to have sufficient thickness to absorb x-rays (e.g., >95%). We have successfully demonstrated Talbot-Lau interferometry operating at 50 keV x-ray energies, which is important for imaging large electronic packages with the three complementary contrasts.

With Talbot-Lau interferometry, three x-ray radiographs with three complementary contrast can be acquired simultaneously: absorption contrast, phase contrast, and scattering (darkfield) contrast.

Results

We illustrate some of the key capabilities of this novel X-ray imaging tool with a System in Package (SIP) which is an advanced semiconductor package. To demonstrate capabilities in imaging MEMs device we used a commercially available *iphone* camera lens. Sidewall delamination failure on advanced package like a SIP is one of the failure modes that currently does not have a good non-destructive solution with conventional imaging tools, such as C-SAM or XRM. Similarly, there is no good solution to visualize cracked Si die within intact packages such as microSD memory devices. Another class of failures include voids within organic layers or defects within low X-ray contrast organic materials located next to highly X-ray absorbing materials such as metal wires, solder balls, copper bumps or vias. Fig 4.

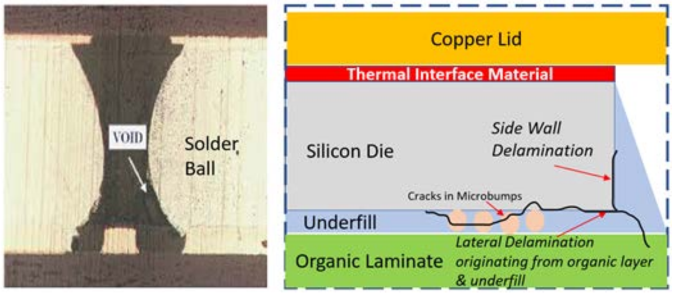

Fig. 4: Failure mechanisms which are challenging for current non-destructive imaging techniques. Image on left is an Optical image of a cross section showing void in underfill next to the solder ball. Illustration on the right shows lateral and sidewall delamination in underfill and cracks in microbumps which are difficult to detect.

A system in package (SIP) has several integrated circuits enclosed in one or more chip carrier packages that may be stacked using package upon package which are connected by fine wires bonded to the packages or through metal bumps. SIP is typically used in mobile phones and digital music players. Sidewall delamination failures on advanced packages like a SIP currently cannot be identified nondestructive with conventional imaging tools, such as C-SAM or XRM.

In fig 5, while nothing unusual can be seen in the X-ray absorption contrast image, the sidewall delamination show signatures of delamination in both phase and darkfield/scattering contrast images.

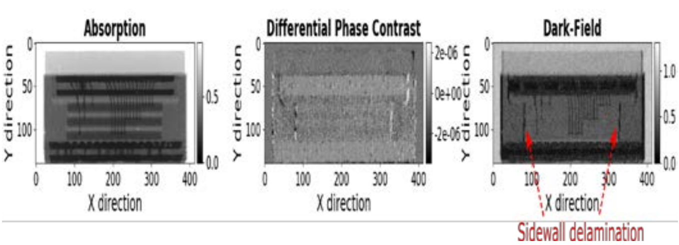

Fig.5. Radiograph of sidewall delamination of SIP showing sidewall delamination in Phase Contrast (middle image) and Dark field imaging (right image) but not in Absorption contrast mode

Note that while we can observe the wires and the different layers of dies in the X-ray absorption contrast (image on left), we cannot discern any delamination between the silicon dies and the underfill. But the delamination is highlighted using darkfield because of the strong X-ray scattering within the crack interface. Likewise, the Phase Contrast image also complements the darkfield defect location.

The next example illustrates the power of Phase Contrast to visualize voids within the organic layer, which typically are not visible with X-ray since voids on organics have very similar contrast. Figure 5

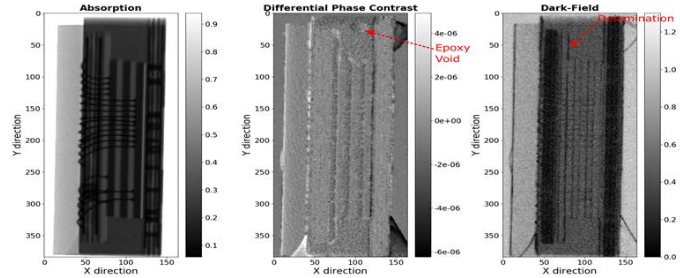

Fig. 5. Image on left is a radiograph of Absorption contrast in SIP. Center image is a Phase Contrast Radiograph where the arrow shows a bubble/void in the organic layer. The image on right shows lateral delamination between the chip and underfill organic layer.

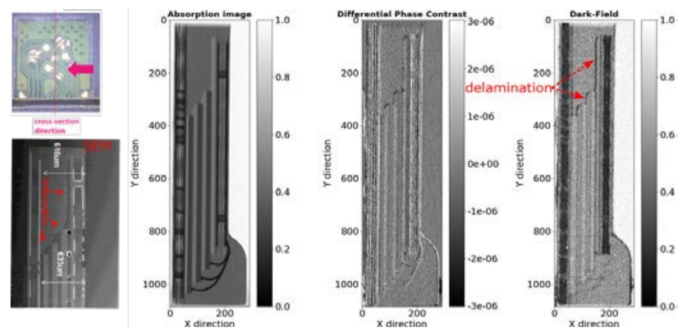

Fig. 6. Radiograph of sidewall delamination of SIP showing delamination in Phase Contrast (third image from left) and Dark field imaging (image on right) but not in Absorption contrast mode (second image from left). Image on left (top colored image is an optical image showing overview of cross section of the package while the bottom image is SEM cross section showing both lateral and side wall delamination along the chip-underfill interface.

Figure 6 shows sidewall and lateral delamination of another SIP and an optical microscope overview with the corresponding SEM cross section of a similar batch of failed samples (image on left). The Absorption image does not show any abnormality while the Phase Contrast and Darkfield radiographs confirm what the SEM cross section is showing for the batch of failed packages.

We did another proof of concept experiment to verify if the novel imaging tool can be used to detect defects in a MEMS device. To do this we purchased an off the shelf commercial camera module typically used in mobile phones. Today's mobile phone cameras consist of some 10 to 20 different components such as plastic or glass molded lenses, pupils, baffles, actuators, lens holders, barrel, filters and the CMOS image sensor. As Si and polymer materials are low Z materials, defects, cracks, voids or alignment issues are challenging to observe with traditional x-ray imaging.
The following result is an illustration on how we may use a combination of X-ray absorption, phase and darkfield contrast to locate voids, cracks or alignment mismatch issues in MEMS based devices such as a mobile phone camera.

Fig 7: Mobile Camera Module complete with lens, CMOS sensors and electronics.

The camera module is imaged under radiograph mode for all three-contrast mechanism. The side and top views are shown in fig 8.

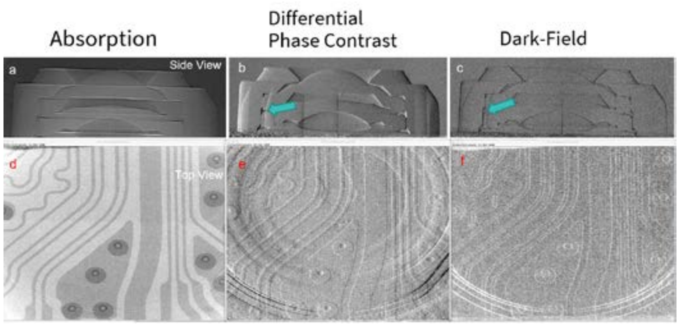

Fig 8: Side view of camera module showing the stack of optical lens in Absorption contrast, Phase contrast and Dark field as radiograph respectively (8a, 8b and 8c). The interfaces and gaps between the SiO2 lens with other components (blue arrow) have much better definition in phase contrast and darkfield contrast than under absorption contrast. Similarly, the top view of the camera (8d, 8e and 8f) shows similar differences in detail. Absorption contrast image, 8d, only picked up the metal traces of the image sensor located at the bottom of the camera. The outline of the lens (concentric lines) together with the metal traces are apparent in phase contrast and darkfield radiographs (8e and 8f)

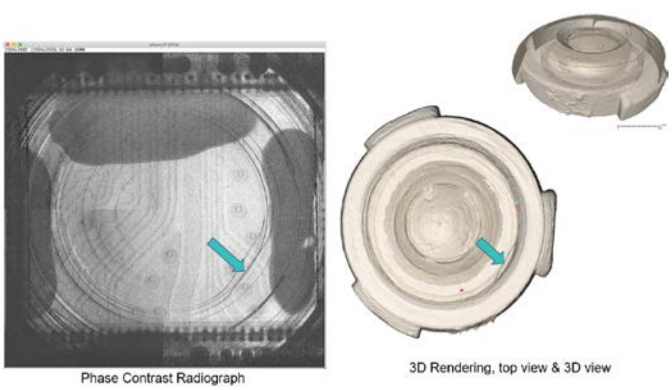

Fig 9: Merging the 3D rendering of the absorption contrast image of the camera lens (images on the right) with the 2D phase contrast image into a composite image (image on left) also help facilitate the location of the void in the camera module (blue arrows).

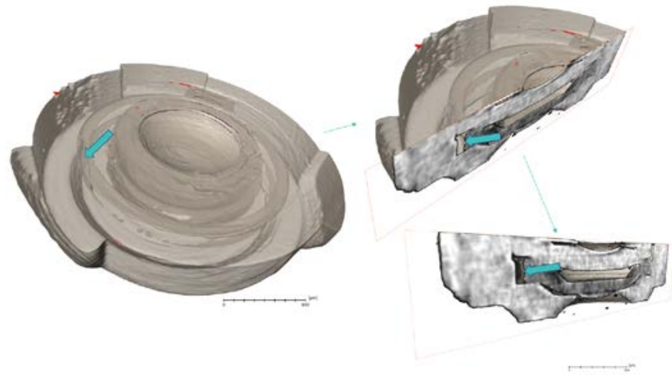

Fig 9: 3D rendering in absorption contrast with a cutout to reveal the large gap or void in the camera module (which was first observed in the phase contrast and darkfield radiographs in fig 8b and 8 c).

The results of scanning the whole camera module under Absorption, Differentiate Phase contrast and Dark field are shown in Figures 7-9. It is apparent the location of the large void or spacing can be rapidly determined using Phase contrast and Dark field even just by acquiring 2D radiographs (compare Fig 8 b and 8c with the final 3D tomography images in Fig 9). This results in the identification of defects &/or mechanical alignment issues previously undetectable with conventional x-ray imaging within minutes. Additionally, the data can be further refined using Artificial intelligence (AI) machine learning for rapid fault localization. Furthermore, interfaces between low Z materials such as SiO2 or polymers, typically transparent to conventional X-ray imaging, can also be easily determined. The ability to quickly and non-destructively visualize void, defects in Si based materials or polymers can be a major advantage with MEMs devices since many of these are related to Si and Si interfaces.

Conclusions

We have demonstrated the power and versatility of the novel XRM with the added capability of Talbot interferometry technique that has three contrast mechanism. Its ability to address challenging failure analysis issues of next generation advanced packages and MEMs devices have been illustrated. Results from differential phase contrast and dark field imaging showed the power to resolve failures which currently have no non-destructive imaging solutions. These include side wall delamination, voids within organics or molding compounds and Si or polymer-based lens in a MEMS type device such as a mobile phone camera. Tomography for 3D imaging using Phase and Darkfield is possible with this technique, but in many cases, it may not be necessary. It is also time consuming and redundant to perform a full tomographic reconstruction to locate minute defects when the defect can be confirmed quickly in 2D. Darkfield imaging is an X-ray scattering technique with sub-resolution power, which means defects, voids, cracks or delamination beyond the native resolution of the system may be detected. Hence cracks or delamination which are submicron in dimension may be visualized in darkfield when the X-ray imaging system is operating even at

3 to 5 micron voxel. As phase contrast and darkfield imaging are additional capabilities to the conventional sub-micron resolution XRM, there is no need to change established workflows to image certain failures within devices if they have been proven effective using absorption contrast tomography. However, Talbot Imaging will be critical to solve the aforementioned failures which currently have no good solutions. Finally, the ability to locate defects even in 2D mode promises to speed up the FA workflow. We envision that phase contrast and darkfield 2D imaging can be further refined with AI machine learning to be able to rapidly localize defects non-destructively, often without the traditional need to collect a complete tomography data set, reconstruction and post analysis which can be very time-consuming.

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