Latest Developments of the X-ray Inspection Technology for PCBAs and Microelectronics Devices

Evstatin Krastev, Ph.D.
Nordson Corporation
CA, USA
evstatin.krastev@nordson.com

ABSTRACT

Traditionally, X-ray technology has been widely used for inspecting optically hidden joints and other features within PCB assemblies and advanced microelectronics components and systems. With ever growing trends of size reduction and higher complexity, the inspection challenges are growing and driving the development and improvement of the X-ray inspection systems. There are two main flavors of X-ray inspection equipment: inline (AXI), and standalone (MXI) systems. Both types of systems offer 2D and 3D inspection techniques. 2D is usually much faster than 3D, but the 3D techniques deliver further inspection capabilities via virtual cross-sectioning techniques. The MXI systems can also be found in the failure analysis labs and offer further analytical capabilities in the form of porosity measurements, solder reflow simulators, and others. Due to their higher resolution and flexibility, in many cases the MXI systems are used to verify the AXI results and fine tune the AXI algorithms. The MXI systems also feature some automation capabilities, but these are less developed and slower compared to the AXIs. There is ever growing demand for the AXI and MXI systems to communicate with each other and with other machines in the SMT line in accordance with the Industry 4.0 smart manufacturing process. This paper provides an overview of some of the latest technical developments in the X-ray inspection technology for the electronics industry.

Key words: PCBA inspection, X-Ray Inspection, CT, Planar CT, AXI, MXI, BGA, LGA, POP, QFN, flip chips, through holes, TSV, Vias, Interposer, Interconnect, CSP, SOC

INTRODUCTION

X-ray inspection (XRI) is widely used for examining optically hidden features and interconnect for the electronics industry. This includes SMT, semiconductor manufacturing, medical devices, aerospace, automotive, etc. The XRI is widely used in product development, quality control, manufacturing process control, yield enhancement and failure analysis. Its unique capability to dissect electronics systems and components without physical intervention has made it an indispensable and widely proliferated technique that is critical to the development and growth of the above industries (Figure 1).

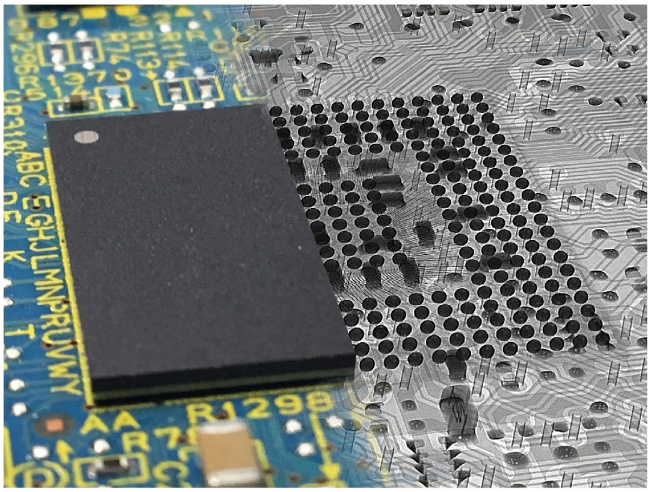


Figure 1. X-ray inspection is used for examining optically hidden features and interconnect in PCBAS, microelectronics devices, semiconductor wafers and panels

The first XRI systems for the electronics industry using electronic X-ray image registration (real time x-ray) started to emerge in the 1980s and developed significantly in the 1990s and 2000s to serve the rapid advances of SMT and microelectronics manufacturing. Two main types developed through the years: MXI (Manual X-ray Inspection) and AXI (Automatic X-ray Inspection) systems. 2D and 3D inspection methods are used in both types (Figure 2).

MXIs are usually offline systems with manual or semi-automatic operation including some fully automatic features. They are also called X-ray microscopes and are usually found on the side of the SMT line or in the failure analysis lab. These systems are characterized with slower operation, but much higher flexibility and usually superior resolution and magnification. The AXI systems are inline systems and are usually found on the SMT line. These systems run in a fully automatic way, thus always need a program to be generated in advance. The important characteristics of the AXI systems are throughput (higher the better), board size, defect detection rate, and false call rate.

Figure 2. MXI, AXI, and AXM inspection systems for the SMT and SEMI industries

An important branch of the AXI family is the AXM (Automatic X-ray Metrology) branch. These systems are usually placed inside the clean room and are used for inspecting semiconductor wafers (300 mm diameter), panels (500x500mm) etc. (Figure 3). These systems have extremely precise movement and high resolution as they are used to inspect wafer level interconnect like TSVs, micro bumps and complex 3D structures. With TSVs size decreasing to 3-5-10 µm diameter and micro bump pitch going down to 25 µm and less, the need for accurate manipulation is extremely important. These systems can output images, but their main output is data. The semiconductor wafer or panel is scanned and using sophisticated algorithms a pass / fail result is delivered for each TSV or micro bump that was pre-programmed for inspection. This includes location, as well as measurement parameters like void diameter or TSV fill percentage. Many other parameters like shape, open joint, shorts, etc. can be also identified and reported in accordance with the particular customer requirements.

As mentioned above, the size of the interconnect and other features is progressively decreasing in size at the same time the complexity of PCBAs and microelectronic components and systems is steadily increasing. In addition, the requirement for speed and more accuracy (high defect detection rate,100% is best, and low false call rate,0 is best, are also steadily growing. The above factors have been driving the development of the X-ray inspections systems through the years and are even more stringent at the present time.

Thus, the modern X-ray inspection system is a very complex machine that includes the X-ray source, detector, sample manipulation, GUI, complex algorithms for automatic defect finding, as well as sophisticated protocols for data output, process control, and machine-to-machine communication. All the above components need to work in synchrony to assure the smooth and efficient operation of the system.

X-RAY DETECTORS

The X-ray image is a “shadow image”. X-rays are created by a point source; a test sample is placed between this source and an x-ray detector. X-rays have the property to penetrate and go through matter in the process of which their intensity decreases due to absorption. Thicker and x-ray denser areas of the sample absorb more of the initial x-rays resulting in areas on the detector with less intensity. These are registered/displayed as darker areas (Figure 3).

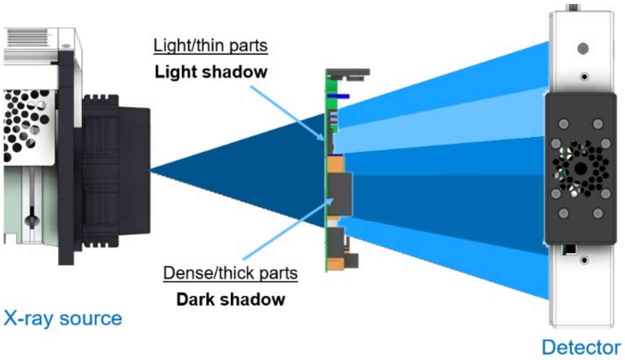


Figure 3. How are the x-ray images created within an XRI system.

Since the very beginning, and up to present day, many XRI systems have been using X-ray detectors developed for the medical x-ray imaging industry. Initially, image intensifiers (II) were used (Figure 4). These are vacuum tube devices that transform the incoming x-ray radiation to electrons. These electrons are strongly multiplied within the vacuum tube using high voltage. The resulting signal is converted again to light and registered using an analog or digital camera and displayed on the computer screen. The IIs are large and heavy devices that are difficult to integrate into the XRI system. They have limited resolution (0.5-2 megapixels) and bandwidth (8 to 10 bits). In addition, they tend to be very noisy, thus the resulting image needs long averaging.

Figure 4. XRI system featuring II detector, the large white tube mounted on the moving arc. X-ray source is on the bottom. Sample is position on a large tray that is placed on the frame. Sample tray is removed in this case in to show x-ray source. The detector moves full 360 degrees around the sample and can incline 70 degrees from the vertical.

The flat panel x-ray detectors (FPD) appeared commercially in the early 2000s, see Figure 5. There was a period of coexistence of IIs and FPDs that were used in the XRI systems. This period lasted about 10 years. Through the years FPDs have undergone tremendous development since their commercial introduction and completely displaced the IIs in the contemporary XRI systems. FPDs have much lower noise and higher bandwidth (14-16 bits) compared to the IIs. These are true digital solid-state detectors and typically have 1 to 6.5-megapixel imaging matrix. Pixel size is usually 75 or even 50 microns. The design principle is very simple. X-ray sensitive plate or film (usually CsI or Gadox) converts the x-rays into light. This is registered by a silicon plate with a matrix of photo diodes. The digital signal is then read using TFTs. CMOS or amorphous silicon is typically used as a base to deposit the photo diode and TFT structures.

Figure 5. XRI system featuring FPD detector, the compact blue box mounted on the moving arc. X-ray source is on the bottom. Sample is position on a large tray that is placed on the frame. Sample tray is removed in this case in to show x-ray source. The detector moves full 360 degrees around the sample and can incline 70 degrees from the vertical.

Despite the simplicity of its principle, modern CMOS FPDs are complex systems that are meticulously designed and engineered. The thickness and quality of the x-ray sensitive plate plays great importance on resolution and bandwidth. Sophisticated lead-infused glass plates are used to protect the thin film electronics from the x-rays but transfer all the available signal. A significant amount of digital signal processing and amplifying hardware is also onboard to maximize speed, bandwidth and resolution of the FPD. All these complex sophisticated sub-systems need to be tightly packaged in a very durable assembly as FPDs are moved within the modern XRI systems at high speeds and accelerations to maximize throughput. Because of all the above factors, some XRI system manufacturers develop and manufacture their FPDs in house in order to optimize them for the electronic industry x-ray inspection, to use the full potential of the device, and to offer top performance.

X-RAY SOURCES (TUBES)

An x-ray tube is a vacuum device that transforms a high-energy electron beam into x-rays and heat. The heat needs to be quickly and efficiently disposed of in order to not burn the tungsten target (the area where the electron beam hits). The first x-ray tubes were developed in the early 1900s (Figure 6).

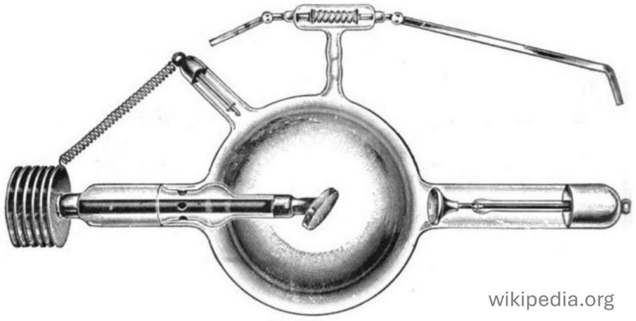
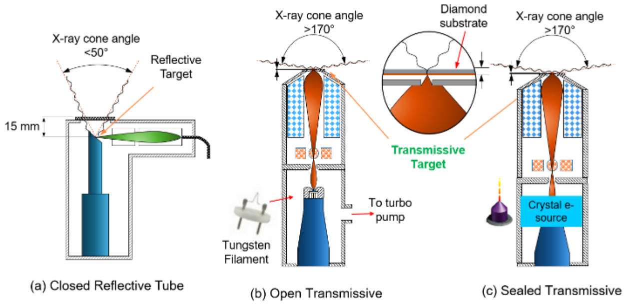


Figure 6. Old x-ray source design 1900s

The main types of x-ray sources that are currently used in the contemporary XRI systems are shown on Figure 7. The sealed reflective tube (a) has a crude but durable filament. It develops high power and a long life, but poor focal spot (resolution) and magnification. Typical focal spot is about 5 microns or larger. These types of tubes are used in lower performance MXI systems and in AXI systems when high resolution and magnification is not necessary.

Figure 7b shows an open transmissive tube. These were developed in the 1980s. It uses fine tungsten filament that needs replacement regularly (every several hundred hours) and to do this one needs to break the vacuum and open the tube. This where the name “open” comes from. This is disadvantage as every time one opens a vacuum system, all kinds of contaminations can be introduced, and the process takes considerable time during which the XRI system cannot be used. The target is a thin tungsten film deposited on a beryllium or diamond substrate. The target is attached to the tube body via a rubber O-ring. This limits the thermal conductivity of the target and requires e-beam defocusing at several watts of power to protect the target. Unfortunately, this results in decreased sharpness/resolution at power levels higher than several watts. Vacuum is generated using turbo and mechanical pumps and is in the region known as high vacuum. The open transmissive tube has much superior resolution and magnification compared to the reflective tubes and are used in high-performance XRI systems. At low power these tubes deliver micron or sub-micron feature recognition, however, when higher power levels are employed, the sharpness and resolution drop significantly.



(a) Closed Reflective Tube (b) Open Transmissive (c) Sealed Transmissive

Figure 7. X-ray sources used in contemporary XRI systems; (a) closed reflective, (b) open transmissive, (c) sealed transmissive

Further development of the open transmissive tube is the sealed transmissive tube (Figure 7c) and were commercially available around 2005. Instead of tungsten filament, these tubes use crystal filament that delivers e-beam with much higher density and stability compared to the tungsten filament. In addition, this filament has a very long life up to 10,000 hours and does not need periodic replacement, which is a significant advantage. The vacuum in these tubes is maintained by very low consumption ion pumps and is in the ultra-high vacuum region. Due to the sharpness and stability of this type of source it delivers the ultimate submicron (0.1 micron) feature recognition.

In the last couple of years, the sealed transmissive tubes have further developed allowing novel methods of target attachment and e-beam control that drastically improves thermal conductivity of the target and eliminates the need of defocusing through the entire power range (up to 20-25 watts on the target). The low heat conducting O-ring has been eliminated. This is an enormous advantage as the x-ray source keeps its sharpness and resolution up to max power, resulting in very sharp and noise free images.

Another very recent development in the sealed transmissive tube technology is the use of so called “structured” target. When ultimate sharpness is needed, the e-beam is pointed to a region of the target that delivers even sharper focal spot and ultimate feature recognition.

3D PLANAR CT (PCT)

As discussed earlier, the complexity of microelectronic components and PCBAs assemblies is constantly increasing. Multilevel 3D packages incorporating micro bumps, interposer and TSVs, systems in a package, and multilayered dense (10+ layers) PCBAs are widely used. The only way to nondestructively inspect these types of devices is the use of 3D Computer Tomography (CT) techniques that include μCT and Planar CT. Let’s consider the following example. Figure 8 shows a high quality 2D image of a very dense 14-layer PCBA. Due to the complexity is difficult to distinguish between the different layers using just 2D techniques. Figure 9 shows virtual non-destructive cross sections of the area of interest obtained using high quality 3D model produced by PCT. Now the area of interest can be dissected and analyzed quickly and effectively. Defects and abnormalities are registered, and high-quality 3D images and virtual cross-sections produced.

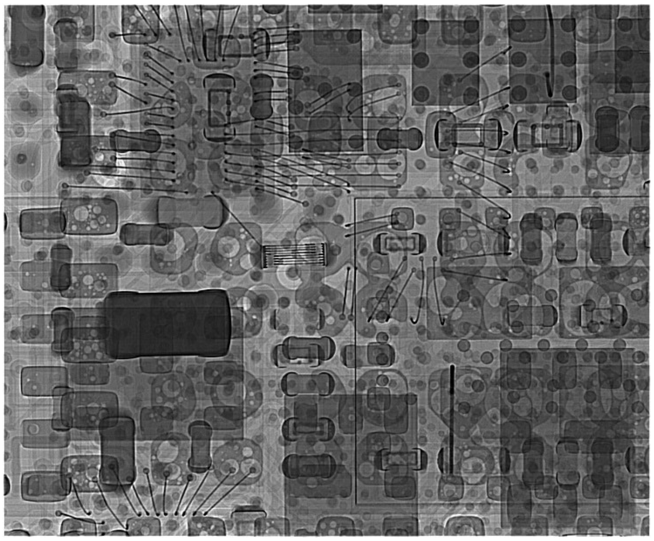


Figure 8. High quality 2D image of a complex multi-layer PCBA. Due to the complexity is difficult to distinguish between the different layers using just 2D techniques.

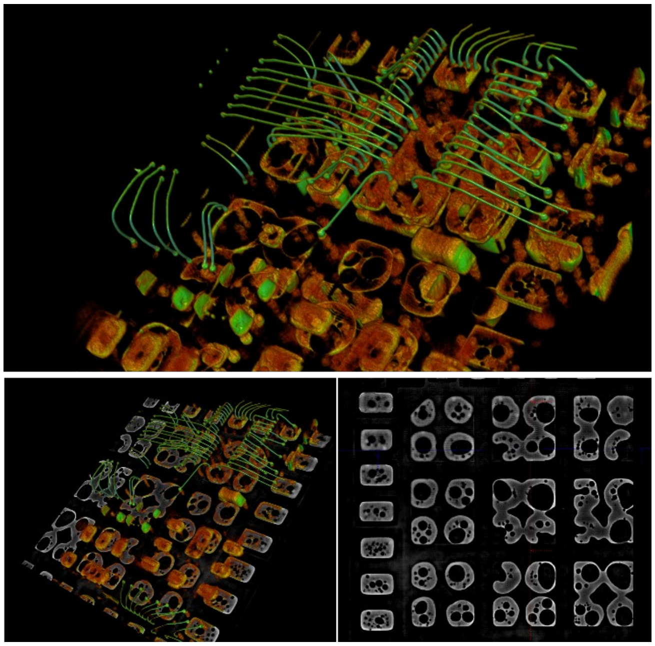


Figure 9. 3D PCT model showing 3D rendering views and sections. Defects and abnormalities are quickly and effectively registered.

PCT is widely employed in the contemporary MXI and AXI systems due to its flexibility, speed and ability to be used on large samples with very high resolution and magnification.

Figure 10. Working principle of planar CT (PCT). PCT keeps the sample flat and rotates the x-ray detector around it. X-ray source is on the bottom.

Both µCT and PCT use similar image processing algorithms. The key difference is that while the µCT technique rotates a small size sample positioned between the x-ray source and detector, the PCT keeps the sample flat and rotates the x-ray detector around it (Figure 10). Consequently, the µCT systems are usually found in the engineering lab. Some of these µCT systems have extremely good resolution, but usually the sample size is limited, the acquisition time is longer, and their operation is not suitable for automation. On the other side, the PCT technique can handle extremely large samples, can have very short scan times, can be automated with a very high throughput, and is widely used in the offline MXI as well as the inline AXI and AXM systems.

Remarkable steps have been achieved improving the image quality and speed of the PCT technology recently, like sophisticated shudder corrections algorithms and dynamic acquisition. The standard PCT technique used in AXI would stop at several positions around the sample and take a 2D image. These few 2D images are used to create the 3D model. We need to keep in mind, that at each position we lose time while the detector is decelerating, stabilizing, and after that accelerating again. In contrast, the Dynamic Planar CT makes a loop around the sample without stopping and collects 50 or 100 2D images in the process. Thus, the resulting PCT model is done in half or quarter of the time and the quality is drastically improved. As a result, the inspection speed, resolution, and defect finding are drastically improved.

ADVANCED FAULT DETECTING ALGORITHMS AND ARTIFICIAL INTELLIGENCE (AI)

The need for automatic defect detection is the main reason for the extensive development of the AXI systems through the years. The idea of removing the subjective, slow, and expensive human operator has been the main driver behind this growth. It is worth noting that some MXI systems also offer limited fully automatic inspection solutions with significantly lower throughput. The first AXI systems emerged in the mid-1990s and were analog systems with low throughput at about 0.21-0.25 square inch per second. Since then, AXIs have sustained significant growth and increased sophistication, delivering drastically improved speed, defect detection rate, and false call rate. This much improved performance was achieved by hardware, system mechanical design and computer developments as discussed above. However, the equally important factor is the explosive development of ever improving defect detecting algorithms that of course were facilitated by the exponentially increasing processing power through the years.

Let's look at simple 2D auto voiding detection (Figure 11) in a BGA. The procedure looks quite simple – the computer needs to find the BGA balls and register the lighter pixel areas within each ball. However, if we think a little deeper, background grey levels could vary significantly within the region of interest and within each bga ball. In addition, there could be other components on the PCB that obstruct the view and make things even more complicated. Thus, even this very simple case needs a substantial level of sophistication in the employed algorithms.

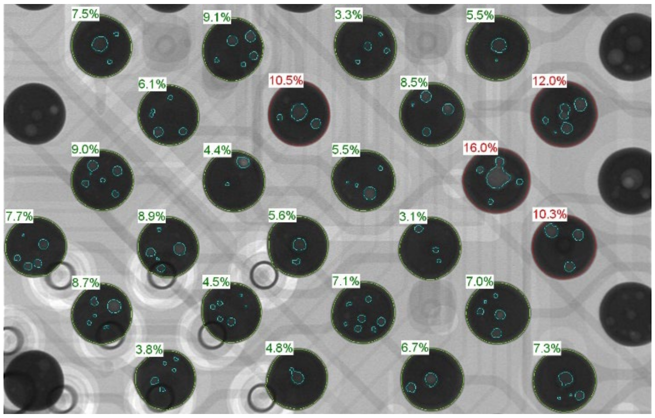


Figure 11. Simple 2D voiding calculations. Substantial level of sophistication in the employed algorithms is needed for fast and reliable operation.

Let's move to a simple AXI example. If we look at the images in Figure 12, the BGA balls look very similar to the human eye. However, each ball is analyzed by the machine algorithms looking for certain signatures that reliably distinguish between good and open/lifted joints.

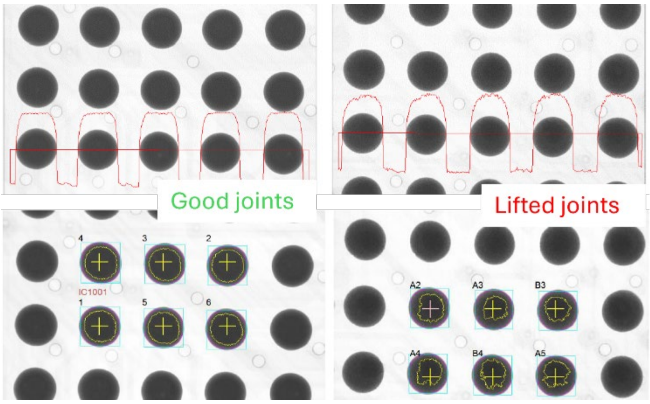


Figure 12. AXI algorithms in action detecting reliably open/lifted BGA joints.

To finalize the chapter on algorithms, I would like to touch the topic of artificial intelligence (AI). We have been talking about AI for many years, but I believe the real breakthrough is happening now. This is due to the computing systems reaching the necessary levels of processing power as well as the development of very sophisticated self-learning intelligent algorithms. We can expect specialized AI modules to become more and more available, both offered for sale by AI companies, or developed internally. These AI modules could be imagined as being a specialized "black boxes" with data inputs and outputs, sophisticated AI engine inside, and including self-learning capabilities (Figure).

CONCLUSION

The x-ray inspection systems have experienced tremendous growth since the 1980s, due to ever-increasing stringent trends of miniaturization and complexity within the microelectronics and SMT industries. 3D packages and multilayered PCBAs have been one of the main drivers in recent years. In order to meet requirements, hardware, including x-ray sources, detectors and system design, has achieved a remarkable upsurge in capabilities. In addition to that, we see an explosive growth in defect finding algorithms. Implementation of AI solutions is the new trend that will become one of the main drivers in X-ray inspection capabilities in the foreseeable future.

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