THE IMPLICATIONS OF RECENT TECHNOLOGY ADVANCES FOR X-RAY INSPECTION IN ELECTRONICS

David Bernard, Ph.D.
Nordson DAGE
Aylesbury, Buckinghamshire, U.K.
david.bernard@nordsondage.com

Keith Bryant
Nordson DAGE
Aylesbury, Buckinghamshire, U.K.
keith.bryant@nordsondage.com

ABSTRACT

Taking x-ray images goes back over 100 years. Since then, there have been numerous advances in terms of x-ray tube and x-ray detector technology and these have been increasingly applied into helping with the manufacturing of electronic components and assemblies, as well as in their failure analysis. Most recently, this has been rapidly driven by the continued reduction in board, device and feature size and the movement to using newer, lower density materials within the structures, such as copper wire replacing gold wire as the interconnection material of choice within components. In order to meet these challenges and those in the future, there have been a number of recent key improvements to the vital components within x-ray systems. In particular, there is a new x-ray tube type that permits high magnification inspection at improved resolution, yet retains high tube power under these conditions, allowing good x-ray flux for inspection of the smallest features. There is also the availability of new and improved x-ray detectors (both image intensifiers and CMOS Flat Panels) that are now specifically designed for electronics applications, rather than hand-me-downs from the needs of the medical market, which are able to take best advantage of these tube developments.

The choice of available technologies, however, means selecting the tube / detector combination which is optimum for a particular electronics inspection application is no longer so clear cut. For example, one configuration may provide certain benefits that are applicable for one area of electronics inspection, whilst being less valid for others. This paper will review the various x-ray tube and detector types that are available and explain the implications of these choices for electronics inspection in terms of what they provide for inspection regarding image resolution, magnification, tube power, detector pixel size and the effects of detector radiation damage, amongst others. It will also suggest optimum configurations for the main electronics inspection tasks required today.

Key words: X-ray inspection, X-ray technology, X-ray detectors, X-ray tube, Sealed-Transmissive X-ray Tube.

INTRODUCTION

The technology available in the current majority of x-ray inspection systems, used for test and failure analysis in electronics manufacturing, has been around for a long time and almost all has been adapted from the technology used in the medical arena. As the numbers of x-ray systems sold for medical applications is much larger than those for electronics then the needs for electronics inspections are placed second by the technology manufacturers and therefore compromises have to be made, making the final systems for electronics inspection non-optimal. For example, image detector sizes of 1Mpixel (1000 x 1000 pixels) are not uncommon, as that is an acceptable level for medical imaging, and so there is little push by detector manufacturers to increase this. In addition, as will be seen later, changing these specifications also comes at a substantially higher price. The alternative option of a complete unique development of new technology specifically for electronics applications, in what is commercially a relatively small market sector, was not followed until recently. In particular, there have been advances in x-ray tube and x-ray detector technologies that now make x-ray inspection systems more fully optimised for the applications seen in electronics manufacturing today, as well as being ready for the increased challenges in the future. For example, the switch to copper wire inter-connects within packages (with their substantially lower density for x-ray imaging compared to gold wire inter-connects) and ever smaller feature sizes, such as in Through Silicon Vias (TSVs) and ever smaller solder bump connections. The improvements that these new technologies offer for x-ray inspection of electronic applications have also to be compared with the existing technology.

X-RAY TUBE ADVANCES

X-rays are produced when a stream of electrons are accelerated so as to hit a metal target within an evacuated x-ray tube. The maximum x-ray energy available is determined by the accelerating voltage applied to the electrons but, in fact, a full spectrum of x-ray energies is produced below this maximum value. To ensure that the electrons hit the target without dissipating their energy, all x-ray tubes are maintained under vacuum conditions. The ultimate resolution of the x-ray tube is dependent on how small the accelerated electrons can be focussed onto the metal target, the position known as the focal spot of the x-ray tube. The smaller the focal spot is then the smaller the area of emission of the x-rays from the target and this defines the best resolution that a particular x-ray tube can provide. There are two x-ray tube control settings for the operator; the accelerating electron voltage applied to the tube (known as the tube kV); and the quantity of electrons that hit the target (known as the target wattage, or possibly as the tube current). The target wattage / tube current indicates the 'brightness' of the x-ray tube with an increase in power meaning more electrons being accelerated in the tube to generate the x-rays. It should be noted that if the accelerating electron voltage (kV) is increased (needed for inspecting thicker / more dense samples) then this will broaden the focal spot of any x-ray tube. This is because the primary electrons will increasingly have more energy that allows them to generate more secondary electrons from the primary impact. These secondary electrons will also impact into the target and generate x-rays, but will do so outside the narrow focal spot of the primary beam and so effectively broaden the overall focal spot, thus decreasing the resolution that can be used for imaging. In addition, increasing the tube power but still attempting to maintain as small a focal spot as possible will substantially increase the energy being put into the target at the focal spot. This extra energy, usually as heat, will have to be removed from the tube otherwise it may damage the target. X-ray tube manufacturers have to contend with these issues in their tube designs.

Closed X-ray Tube Type

The earliest form of x-ray tube still used today is known as the closed tube type because the necessary vacuum is produced during manufacture. The closed tube design goes back to the discovery of x-rays over 100 years ago and the current incarnations are still based on the same fundamental principles. The tube is sealed and cannot be opened for servicing. This approach fundamentally limits the resolution that this type of tube can practically achieve because the smallest achievable focal spots would place huge energy density into the target which will result in target damage after only a limited time of use. Therefore enhanced resolution is not practical from this tube type as you are unable to change the target, once damaged, because of its sealed nature.

A schematic of a typical closed tube used today is shown in figure 1. The closed tube typically uses what is called a reflective target which means that the x-rays are only visible from the incident face of the target. The result of this type of design is that the focal spot is far away from the window where x-rays are emitted from the tube (i.e. out of the vacuum enclosure) thus limiting the ultimate available magnification and usable x-ray cone (angle of x-ray emission see figure 1). This is because the geometric magnification that an x-ray inspection system can achieve is defined as the ratio of the (distance from the focal spot to the detector) divided by the (distance from the focal spot to the sample). Therefore, the closer the sample is to the focal spot then the greater the available magnification that the x-ray inspection system has. Owing to design / manufacturing considerations, a closed tube inherently has a large focal spot to sample distance, which cannot be reduced. Therefore, the available magnification from this tube type will be limiting for the ever decreasing size of electronic components and their features. In addition, the limited resolution it can achieve, because of its design, will further limit its imaging capabilities. By keeping within a lower magnification and poorer resolution regime, closed tubes can operate for many years. However, their performance does degrade with time and eventually the closed tube has to be replaced at an appreciable cost. Today, the x-ray inspection systems for electronics that are available at lower specifications and lower costs still use closed tubes.

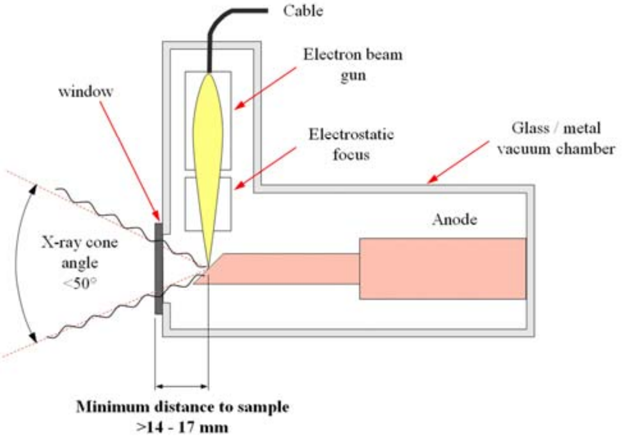

Figure 1. Schematic of the Closed X-ray Tube Type

Open X-ray Tube Type

The next development in x-ray tube types used for electronics is called the open tube type (sometimes called the de-mountable type). The origin of this tube type goes back more than 50 years. It is called an open / demountable tube because it can be opened for servicing, as the necessary vacuum is produced locally through vacuum pumps. Today's open tubes are not too dissimilar from the original versions. As the tube vacuum is produced locally, it means the tube can be opened for the necessary servicing tasks which include filament replacement and target rotation / replacement, which the closed tube does not allow. A different target configuration to the reflective type is typically used in open tubes for electronic applications. This is called a transmissive target as the target material (usually tungsten, W) is deposited on the inside of the x-ray window (see figure 2). This allows the focal spot of the tube to be placed much closer to the sample than with closed tubes (and is practically limited only by the necessarily robust thickness of the x-ray window). Therefore, the geometric magnification for a system with a transmissive tube is much, much greater than with a closed tube. In addition, the focal spot can be reduced in size to improve the tube resolution, subject to limits determined by the target material's ability to dissipate the resultant heat from the electrons as they hit the target. This is because any potentially damaging effects on the target from this improved resolution (smaller focal spot = higher energy density at the focal spot) can be overcome by the ability to rotate the target periodically, thus providing fresh material for x-ray generation and / or replacing the target as necessary.

So far we have discussed the improved resolution of the open tube due to a different target design compared to the closed tube. (See figure 2 and reference [1]). In addition, a different electron source (tungsten filament) is incorporated into the open tube design. This permits the electrons to be produced from a smaller locus within this type of tube when compared to the closed tube. The resolution limit for the open tube is effectively determined by the minimum bend radius that the filament can be manufactured with. It is not possible to make a point filament, as that would burn out very quickly, and so a trade off is made against the minimum bend radius achievable against a realistic filament lifetime.

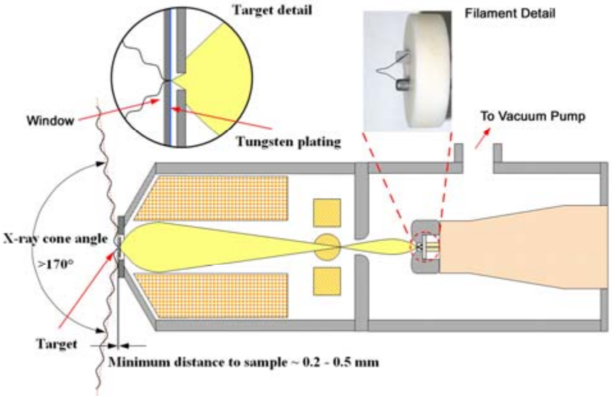

Figure 2. Schematic of the Open X-ray Tube Type

These design trade-offs mean that it is still necessary to vent the x-ray tube to atmosphere, in situ, every few hundred hours in order to replace the filament that provides the electrons in the tube. Once the filament has been replaced, then it is necessary to wait for the vacuum level to recover before operating the tube, as otherwise it will shorten subsequent filament life. In addition, there is a risk of contamination getting into the tube every time venting occurs, particularly in a less than perfectly clean production environment. If contamination does occur then it can cause all sorts of problems to the performance and lifetime of all subsequent filaments in that tube and perhaps, at worst, damage the high voltage electronics, a major cost item. As a general comment, because the filament and target can be replaced, it allows its operation in a deliberately 'damaging' manner to enable better focus of the electrons on the target, so as to give better resolution from the open tube compared to the closed tube.

Whilst the filaments and targets of the open tube can be continuously replaced to renew the best capabilities that this tube type offers, the costs of doing so are not just simply the cost of the filament and target. There is also a further cost of ownership that is more difficult to calculate which must consider the costs of replacing / servicing the vacuum components of the tube, as well as the cost and time of the people needed, on-site, to do this work plus the lost opportunity costs for having a system out of action and therefore not able to inspect the production quality. All these costs over the lifetime of the open tube assume that no contamination gets into the tube at each filament change / service visit / etc. If this were to happen then this can damage the tube, filament and / or the control electronics by causing flash-overs, for example, that may damage the tube permanently.

It should also be noted regarding open tubes that, contrary to many open tube specifications available in the market, the best open tube resolution is only available at a limited tube power. This is because the electron emission from the tungsten filament has a limited angular intensity that can be focussed by the tube electronics onto the focal spot. Achieving higher tube powers requires more electrons to hit the target. This can only be achieved by accepting more electrons from a broader area of emission, which results is a much broader focal spot and therefore decreased resolution of the tube. Sometimes the maximum power of an open tube stated on a system specification sheet is for when the tube is configured for this high power, yet much poorer resolution, configuration. Such a configuration would be typically set when an open tube is used for more general Non-Destructive Testing (NDT) applications, such as inspection of metal castings, for example. If this 'high power / poor resolution' configuration is applied to, typically, thinner and less dense electronic samples then it is likely to quickly saturate the detector and not provide a suitable image, as there is insufficient absorption in these samples to handle the increased quantity of x-rays, even if the poorer resolution were adequate for the inspection task.

Whichever open tube configuration is used ('high resolution / lower power' or 'high power / poorer resolution') then consideration must be given to the needs of dissipating the substantial energy density placed into the tube focal spot (certainly if it is only cooled by air convection). If kept unchecked, such energy densities could puncture through the thin transmissive target, which also acts as the vacuum seal, and thereby cause the open tube to fail. When sub-micron feature recognition levels are required of open tubes - which is typically all of the time for the needs of electronics inspection! - the actual achievable power at sub-micron feature recognition from open tubes is nowhere near the values that 'high power configuration' open tube can achieve. These higher tube power settings mean >> 1 micron feature recognition of the tube (typically 5 – 20 micron or worse) and this will compromise the fine detail quality in the images. The majority of 'high end' x-ray inspection systems use open tubes today. However, as the features of electronics have got substantially smaller over the last 50 years, then open tubes may be at their limit for the inspection requirements needed for electronics today and in the future. For example, the needs of inspecting smaller CSP solder bumps, smaller interconnect wires and tracks, TSVs and copper pillars require something better.

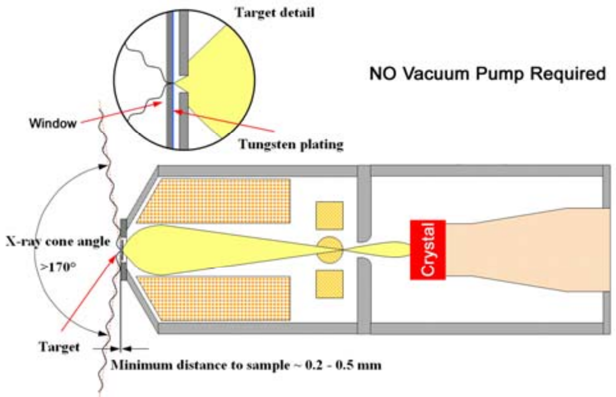

Figure 3. Schematic of the Sealed-Transmissive X-ray Tube Type

Sealed-Transmissive X-ray Tube Type

In the last 8 years, a third type of x-ray tube has emerged and which was designed specifically for the demands of electronics inspection. This is the sealed-transmissive type of tube (see figure 3). It has the sealed vacuum of the closed tube types, which means it has a very long operating life that is measured in many thousands of hours before requiring a replacement. In addition, this tube type has the transmissive target of the open tube, which provides the highest magnification need for electronics inspection. Where the sealed-transmissive tube differs from the open tube is that it generates the required electrons from a special crystal rather than from a filament. As the crystal has a higher angular intensity, it allows the focal spot of this type of tube to be much smaller than can be achieved with an open tube. Furthermore, the tube design and controls have been optimised such that any broadening caused at higher kV settings is maintained to keep within a sub-micron feature recognition limit, even up to 160kV levels. Finally, careful design allows this high resolution, to be achievable over higher power levels compared to open tubes. For example, sealed-transmissive tubes can achieve up to 4W of tube power yet still retain 0.1 micron feature recognition and they can also achieve up to 10W of tube power at ~ 1 micron feature recognition, something that the open tube type is not able to achieve. Eventually, after many thousands of hours of x-ray operation, the whole tube needs to be replaced and this has a reasonable cost of ownership that is of a similar order to that of the open tube over its lifetime. However, there is no maintenance required to the sealed-transmissive tube during its lifetime and there is no need to vent the tube to the atmosphere. Overall, it is difficult to compare the real cost of ownership of a sealed-transmissive and open tube over their lifetime, as the cost basis is different. There are many hidden costs with the open tube (assuming no contamination occurs) which perhaps are not immediately obvious. Anecdotally, it has been seen that the lifetime costs of the open and sealed-transmissive tubes are broadly similar but it is the unknown potential costs of poor filament change / service to the open tube that cannot be easily factored into a cost of ownership model. As feature sizes in electronics continue to shrink and new inspection demands come in, such as TSVs and smaller components / interconnects, then the sealed-transmissive-tube becomes ever more necessary for electronics applications.

Figure 4. X-ray inspection system with image intensifier (II) detector seen above a sealed-transmissive x-ray tube (sample not present). The detector is held in a cradle mechanism that allows oblique angle x-ray views to be achieved without losing the available magnification on the sample.

Figure 5. X-ray inspection system with wafer-based-silicon flat panel detector (w-FPD) seen above a sealed-transmissive x-ray tube (sample not present).

X-RAY DETECTOR ADVANCES

It is not possible to view / measure x-rays directly. It is necessary to have the x-rays affect some intermediate medium which can then be analysed to provide an image. This is why the only way of obtaining x-ray images originally was by using x-ray sensitive film. However, the overhead costs, use of wet chemistry and the time needed for developing the film mean that it is not a useful approach for real-time electronics inspection. Instead the detectors used in x-ray inspection systems for electronic applications have been those that, like the tubes, were originally developed for the medical market. So, historically, the detectors provided for electronics inspection have been defined and developed for another purpose rather than for itself. This is because the much larger medical market has reduced the manufacturing costs of these detectors and from which the much smaller electronics market can benefit, all be it at the expense of capabilities that are not optimised for its needs. This has meant that the detectors used for electronics inspection have been either an image intensifier (which will subsequently be referred to as an II - see figure 4 for what an II looks like when in an x-ray inspection system) or an amorphous-silicon based flat panel detector (which will subsequently be referred to as an a-FPD). More recently, a new type of flat panel detector has become available. This has been specified and developed with the needs of electronics inspection in mind. This differs from the amorphous-silicon type and is called a wafer-based-silicon flat panel detector (which will subsequently be referred to as a w-FPD) – see figure 5 for an example.

The choice of which type and style of detector to use in the x-ray system for the best inspection of different aspects of electronics is not so clear cut. There is the need to consider the relative advantages and disadvantages of using an II compared to a FPD and, thereafter, if the FPD is most appropriate then to look at the differences offered between the a-FPD and the w-FPD types. To ensure that the best detector choice is made for a particular electronics application, the following aspects of the detector's performance needs to be considered:

- Detector image size, resolution & image acquisition speed
- The effects the detector has on the geometric & system magnification of the inspection system
- Detector gain, image contrast & image noise effects
- Radiation damage & detector lifetime issues
- Detector price and replacement cost

Detector Operation

Before considering each of these aspects further, it should be recognised that both the IIs and the FPDs initially work in the same way. Both convert any in-coming x-ray photons, which have passed through the sample, into different wavelength photons (usually visible wavelengths) by using a phosphor material on the input to the detector. The most commonly used phosphor material for electronics applications is Caesium Iodide (CsI), although other materials are possible, such as Gadolinium Oxysulphate (Gadox). Once the x-ray photons have been converted into visible photons by the phosphor material, indicating the position of the incoming x-ray, then the operation of the II and FPD diverges.

With the II, the visible photons are converted into electrons, amplified by an electron tube, converted back to photons on a second phosphor screen and then imaged on a charge-coupled device (CCD) camera, the results of which are presented on-screen to the operator. The brighter the point on the image then the more x-rays were received at that particular location on the II, which, in turn, indicates that that portion of the sample was of lower density, as it prevented few of the x-rays from being absorbed in their passage through the sample. So this is the reverse of a typical hospital (film) image – i.e. bright areas correspond to low density material (e.g. circuit board) and dark areas correspond to high density material in the sample (e.g. solder balls in a BGA). The maximum image size presented to the operator is determined by the size of the input window on the II. The resolution of the image is determined by the size of the pixel elements of the whole detector. The image acquisition speed of IIs is typically 25 frames per second (fps), or greater, before any real time image enhancements may be applied in software / hardware so as to improve the final image quality for best analysis. This is often called 'real-time' imaging. Once image enhancements are applied then this may reduce the acquisition frame rate. Typical image sizes for IIs used for electronics inspection are 0.3 Mpixels, 1.3 Mpixels and 2 Mpixels.

With the FPDs, the visible photons from the phosphor impinge upon an array of CMOS-junction nodes patterned in the silicon (either on an amorphous Si substrate for an a-FPD or on a wafer-based Si substrate for a w-FPD). The amount of visible photons hitting a particular CMOS node will increase the charge build-up at that node. By reading the charge level at each node in the array at a repeat frequency, the respective charge level in each can be displayed as a brightness level and so an image can be produced. More charge at a node provides a brighter response and relates to less dense material in the sample at that position. The maximum image size presented to the operator is determined by the number of pixels in the CMOS area array. The resolution of the image is determined by the size of the pixel elements within the area array. The image acquisition speeds of FPDs can be 4 fps, 10 fps or 25 fps (or greater) and varies between a-FPD and w-FPD types. These acquisition speeds assume that the whole of the CMOS array is interrogated at the frame rates shown. However, it is possible to operate some of these slower operating FPDs in what is called a 2 x 2 binning mode. In this mode, only 1 node (pixel) in 4 is read at every interrogation cycle. As a result, binning speeds up the acquisition rate by up to 4 X and this may be indicated in system specifications. Unfortunately, the price that is paid for using this binning technique is that the resolution of the detector is halved. So a 'binned' detector may be obtaining an image more quickly but the detail of the image is compromised, which is of concern when inspecting the smaller features that need to be seen in electronic samples. It is thought that 10fps is the minimum frame rate that is required to allow realistic 'real-time' imaging for electronics. Detectors that require binning to achieve even this rate may be deemed unacceptable for electronics inspection as, if they are maintained at their non-binned rate, it may lead to much slower inspection times in order that the imaging can keep up with any sample movement. This, in turn, may impact on inspection times and sample throughputs. Typical image sizes for FPDs for electronics inspection are 1 Mpixels, 1.3 Mpixels, and 3 Mpixels.

The choice of which detector type would be appropriate for a particular electronics application depends on a number of additional factors. Both IIs and FPDs have advantages but they also both have limitations. These factors must be considered, not just in relation to each other, but also in relation to the variety of detectors available in the market of the same generic type to ensure the best inspection level is available. Not all IIs are the same and neither are all FPDs.

Magnification Effects

All image intensifiers tend to be roughly columnar in shape (see figure 4) and x-ray systems are limited in size for the practical purposes of installation and maintaining a modest footprint for a good sample size yet with an enclosing cabinet that provides all of the necessary radiation safety. Therefore, this defines the maximum distance that the phosphor of the detector can be placed away from the focal spot of the x-ray tube. In contrast, the flat panel detectors, by their very name, do not have the same vertical height as the II (see figure 5). Therefore, it is possible to place an FPD further away from the tube focal spot in the same design / size of x-ray safety cabinet. As the distance between the tube focal-spot and the detector input is one of the key parameters that defines the geometric magnification that an x-ray system can achieve, then for the same system cabinet design an FPD based inspection system will possibly have a much greater geometric magnification specification than for an equivalent II based system.

However, there is an alternative method of indicating the available magnification of an x-ray inspection system. This is called the system, or total, magnification. This value is a combination of the geometric magnification together with the physical size of the detector and the size of the display unit that presents the final image to the operator. The system magnification is the ratio of the size of the actual object compared to the size of that object when it is presented on the operator display (see reference [2]). Therefore, having a larger operator viewing screen increases the system magnification that can be achieved on a specification sheet, but the resolution of that screen is usually the same as a smaller version and therefore no additional analytical information is provided to the inspector. However, the physical size of the active imaging areas used in the two detector types is different and this does affect the level of system magnification that can be achieved. The typical II inspection area in the systems used for electronics tends to be circular in shape and around 100 mm in diameter. Larger diameter (and usually more expensive) image intensifiers are available but the level of curvature of the input of the detector in these bigger intensifiers is usually too distorting for electronics analysis and so only a smaller section (100 mm or a smaller diameter) within the larger area is actually used for the imaging. The size of the imaging elements that will be shown to the operator are determined by the size of the pixel elements at the face of the II which are imaged by the CCD camera used in the II. Typical pixel element sizes range from ~ 45 x 45 µm and upwards. CCD cameras continue to be manufactured with ever more pixels. However, most monitor screens have a far more limited resolution. So once you exceed the number of pixels that can be displayed in native resolution on screen (i.e. one to one) then any extra pixels will not be shown and the final image will be an average of the extra pixels. This is why there are not the same image sizes in x-ray inspection as would be expected with phone and digital cameras.

The FPD active areas, in contrast, tend to be much larger than for IIs. Typical FPD sizes available for electronics are around 130 – 150 mm by side, or larger. The CMOS array in the FPD then covers this area. As the detector is larger, it means that the pixel element size is larger than for IIs. Typical pixel element sizes in FPDs available for electronics range from ~ 75 x 75 µm to ~ 200 x 200 µm. If more pixels are required in the detector then it means that the area of the CMOS array has to be larger. However the bigger the silicon area then the more substantial the manufacturing costs, whether it is amorphous-silicon or wafer-silicon based. This is why higher quality FPDs are more expensive than IIs. Some smaller FPDs do exist but their performance may not be comparable to the larger panels in terms of speed of operation and image resolution. As with all x-ray inspection, the capability required for a particular application should always be checked on real systems with real samples – and not just against a specification sheet.

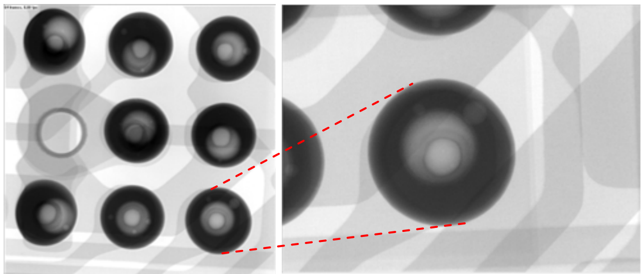

Figure 6. Maximum magnification images (no digital zoom applied) of the same location in a cell phone sample with 300 µm diameter BGA solder balls made on similar x-ray systems. Left image was taken with a flat panel detector (FPD) positioned ~ 20% further away from the tube focal spot than with the image intensifier (II) shown on the right image. FPD system (left) has greater geometric magnification but less system magnification than the II system, even though the detector is further away from the tube.

The net result of the larger size of the FPDs imaging area compared to the IIs is that the system magnification of an x-ray system with an FPD is much less than for the equivalent system with an II, even though the II is closer to the tube focal spot than the FPD. So, confusingly, in system specification terms, an II based system can have less geometric magnification but greater system magnification than for an equivalent FPD based system. So although in specification terms the II based system may seem less impressive than an FPD version, the II based system will provide more real magnification on-screen. An example of this difference in the real magnification available for analysis by having a different detector type is shown in figure 6. Figure 6 shows x-ray images of the same BGA in a cell phone board (300 µm diameter solder balls) inspected at maximum magnification in two x-ray inspection systems that were identical except for the fact that the FPD used in one was ~20% further away from the tube focal spot than the II used in the other system. In geometric magnification terms, the FPD system has a higher value than the II system but as can be seen in figure 6, the II image has more real magnification on screen in the final image. This difference of capability may be important when deciding what detector is best for a particular electronics application. It should be noted that as the thickness of the board increases (for example, having second-side components) then the difference in the maximum available magnification will be less than that shown with the thin board in figure 6. To compensate for this lack of practical magnification, some companies are able to provide a 'digital zoom' function on their imaging software. However, like an optical digital camera running in 'digital zoom' mode, the results of the final 'zoomed' image may be less acceptable and useful analytically, as you are displaying less of the original pixels and 'pixelation' within the image may occur. Having more pixels in the FPD detector to start off with perhaps gives you more scope to use the 'digital zoom' to better effect, but the additional cost of these larger detectors may also have to be considered.

Detector Gain, Image Contrast and Image Noise

Apart from the effects on the available on-screen magnification, the choice of imaging detector also has implications for x-ray tube functionality as well as an impact on the speed of imaging, speed of inspection and sample throughput. This is because of the way the two detector types work. The II has high gain for the quantity of x-ray photons (x-ray flux) that strike its phosphor. The FPDs, however, have much lower gain than the II. In other words, the II will indicate a much brighter signal for the same level of x-ray flux compared to the FPD. Therefore, to get good contrasted images for analysis, the FPDs have to operate with much more x-ray flux and this can only be achieved by increasing the power of the x-ray tube. However, as has been described earlier, increasing the power in certain tube types has to result in a reduction of the tube resolution. The reason why FPDs are attractive for electronic applications is that they tend to have more native gray scale sensitivity (bits) in their images than IIs, which means that features with low and subtle density differences will be better imaged with them. FPDs also have much less noise in their images compared to IIs; however require much higher tube power to be used. This means that much less image averaging needs to be applied to the FPD images to improve / smooth the image quality for best analysis, when compared to using an II. If good quality analytical images can be produced more quickly then this will speed up inspection times and so increase sample throughput. An example is shown in figure 7, where the same BGA has been imaged on similar x-ray systems but containing different detectors as in figure 6. The FPD image was created in only a few seconds and has slightly better contrast depth (as seen in the quality of the joint interface areas within the BGA balls when compared to II produced image). In comparison, the II image took a few tens of seconds to produce such that more images could be averaged to improve the signal to noise ratio from this noisier detector. However, the nett result is that both images for this sample look broadly similar (and the differences are less easy to see in a printed version of the results, but on the x-ray system monitor itself the differences would appear greater). This difference would also become more visible if less averaging time was permitted for the II image, perhaps as would be the case if there is the need for greater sample throughput in a production environment.

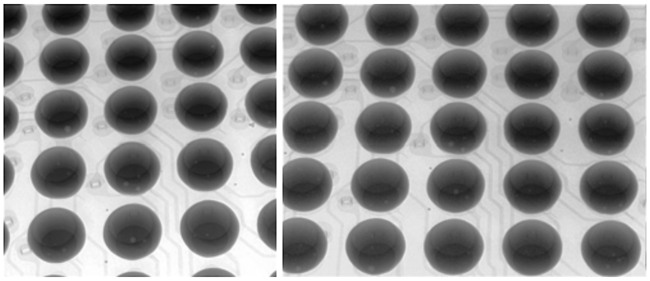

Figure 7. X-ray images of the same location under a BGA made on similar x-ray systems. Left image was taken with a flat panel detector (FPD) and the right image with the image intensifier (II) system. FPD system (left) has greater contrast depth and was achieved much more quickly than the II system image because of the better gray scale sensitivity and lower noise within the FPD. However, the x-ray tube had to be operated at a higher tube power than was necessary with the II system. *(Note: images will look much better on the screen of the x-ray system than when reduced in size and resolution to fit this format.)*

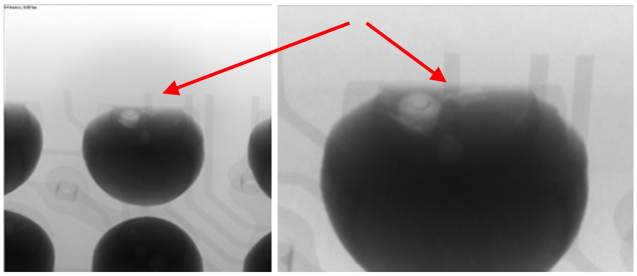

Figure 8. Flat panel image (left) and II image (right) of the same BGA showing a crack at the interface. The contrast of the FP image is superior but the lack of magnification would make this flaw less visible when compared to the II image.

So the trade off between magnification, gray scale sensitivity and image noise may suggest that the FPD is more appropriate for many applications in printed circuit board assembly (PCBA), even though the detector is typically more expensive to manufacture and supply than an II. However when the highest magnification images are required for inspecting the very smallest features then the balance may return to preferring an II as the detector. An example is shown in figure 8, where although the II image took longer to acquire, the detail of the crack in the BGA ball is much clearer in the II image for this example because of the increased on-screen (system) magnification that that the II detector offers.

Effects at Highest Magnifications

In addition to the geometric / system magnification variations caused by which choice of imaging detector is used, a further consideration must be made if the inspection application is related mainly to the analysis of thin samples with very small features that need to be inspected at the very highest magnifications. The most obvious example today is for the inspection of through silicon vias (TSVs) in semiconductors. Whilst the FPD may, or may not, have adequate magnification for the required inspection task, the physical size of the imaging elements, when compared to the much smaller elements in the II, further reduces the image quality from an FPD at the very highest magnifications. This can be explained as shown in figure 9, where the same sized, small feature is imaged on detector arrays with increasing imaging element size. A detector with the smallest imaging element size, such as that found in the II, allows the best resolution images to be produced as it is able to best utilise the ultimate resolution available from a sealed-transmissive tube, for example. As the element size increases, to such as those seen in the FPDs, then the imaging detail of the smallest features is reduced, or perhaps even completely unavailable. The larger the element size then the poorer the detail at the highest magnifications.

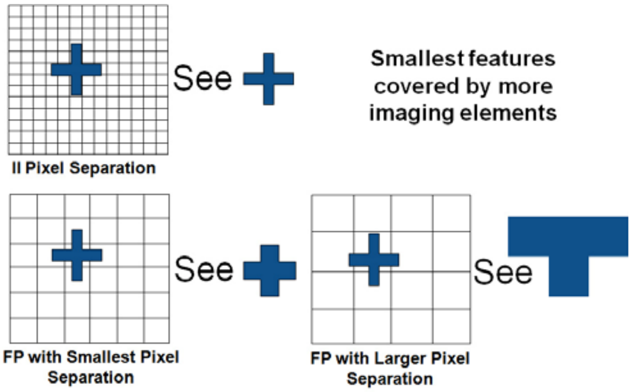

Figure 9. Schematic Representation of the Effect on X-ray Image Detail Quality as the Size of the Imaging Elements in the Detector Increases.

Radiation Damage and Detector Lifetime

As the original II and FPD technologies were initially developed for the needs of the much larger medical market rather than for electronics, the effects of radiation dose on the detectors is a topic that must also be considered when deciding which detector type to use. In medical applications, the desire is to get the best imaging information at the lowest radiation dose to the patient. This is not a primary consideration when inspecting electronics, although for certain components it may be an issue that must be taken into account during production (see reference [3]). In electronics inspection, the sample, and therefore the detector, is continually being exposed to radiation and so adding to the total radiation dose that the silicon-based CMOS detector elements will see. With II detectors this is unlikely to be an issue, as it may be considered that for electronics applications they are radiation hardened and the II is likely to last the lifetime of the x-ray inspection system. The only effect that may be seen over time with the II is a slight and slow degradation of their efficiency that can usually be compensated for by using slightly higher tube powers to increase the x-ray flux. This should not impose any limit on the x-ray tube in a system as the high gain of the II means it is well within the capabilities of most x-ray tubes. However the effect of radiation dose on FPD detectors and the implications is a different matter.

Si-based devices are potentially damaged by radiation. However, the radiation dose typically seen by a PCB during x-ray inspection is orders of magnitude less than the level that will cause any problems for the majority of components and boards (see reference [3]). However, as the FPDs are CMOS nodes that are made from Si, they are exposed to radiation every time they are used for imaging which means the radiation dose builds up over time and the damage mechanism on silicon is cumulative. In medical applications, the likely lifetime radiation dose that the FPD will see is probably much less than the critical limit the FPD can absorb. This is not the case when the FPD is being used for electronics x-ray inspection. As the CMOS array sees more and more radiation dose then more nodes / lines in the array will continue to fail. These failure mechanisms are caused by:

- Increasing electronic noise in the detector
- The failure of extra pixels and lines from damage to, particularly, the amorphous silicon
- Darkening of the produced images due to scintillator burn-out.

These failure modes mean that the majority of FPDs currently used for electronics (usually of the a-FPD type) will have to be replaced after possibly only a few years of use. The replacement cost of the (a-)FPD detector may need to be factored in to the overall system cost of ownership if such a detector is chosen. It should be noted that there is already a moderate level of failed pixels / lines in all FPDs from their manufacture. Attempting to reduce this is difficult, as permitting an acceptable level of missing pixels / lines helps the manufacturing yields and reduces the FPD costs - because there is less wastage of the large areas of manufactured silicon required for the detector. These initial failed elements are removed / compensated for in the system imaging software and are typically not seen in the final image presented to the operator.

It is difficult to say how long an a-FPD type detector will last in operation, as that will depend on the time taken to reach the critical dose level for that detector - at which time the detector is no longer fit for use. This timescale will be influenced by the settings used on the x-ray tube and the separation distance of the detector from the x-ray tube in the x-ray inspection system. As radiation dose, in simple terms, scales linearly with x-ray tube power, then the more tube power that is used then the more radiation dose that you are exposing the detector to. As mentioned above, because the gain of all FPDs is low compared to the II then the operator is typically always using much higher tube powers during inspection with a FPD based inspection system (ignoring the effects this might have on the resolution of the open type x-ray tubes). Therefore, when using an FPD for electronics you have to increase the dose rate that the detector will see in order that there is sufficient x-ray flux to make a good contrasted image (even when using software image enhancement techniques) and this will shorten the lifetime of the FPD. This approach assumes that the x-ray tube used can provide sufficient tube power (and retain necessary resolution?). To try and overcome the high power / loss of resolution limitations described above, it may be thought attractive to move the detector closer to the x-ray tube. This approach will certainly provide much more x-ray flux to the detector at a given tube power setting because the radiation flux increases with the inverse square of the distance. Unfortunately, the radiation dose also increases with the inverse square of distance from the tube. This would mean, for example, that if the detector was moved three times closer to the x-ray tube this would allow 9 X less tube power to be used to achieve the same gray scale level compared with the detector located at the farthest position. Whilst this seems beneficial, it must be remembered that at this closer position the detector would also be receiving 9 X the radiation dose rate and therefore will reach the critical dose limit for the detector, requiring replacement, 9 X more quickly. Moving the detector closer to the tube also ignores the fact that the geometric magnification the system can achieve will be substantially reduced and perhaps limits the analysis that can be performed.

The effects of the detector pixel size and an understanding of the radiation dose damage to a-FPDs are the reasons why the most recent detector development, undertaken with the needs for electronics inspection in mind, resulted in the availability of the w-FPD detector. In addition to having a lower level of manufactured missing lines / nodes and smaller pixels compared to the a-FPD type, it also has, in some versions, a built in lead-glass light pipe between the phosphor and the CMOS array. This light pipe does not stop the visible photons generated at the phosphor from the incoming x-rays from being detected but it does stop the damaging x-rays reaching the CMOS array. It acts like a ‘lead apron’ that is worn by hospital staff when taking diagnostic x-rays and protects the CMOS array from the radiation damage. This approach allows some w-FPD detectors to last many times longer than the a-FPD type in equivalent operation. If the a-FPD type only lasts for a few years before it needs to be replaced, then these costs would need to be factored into any cost of ownership model for such an x-ray system. Such a consideration would be much less likely to be needed for a w-FPD type which has embedded protective lead-glass shielding

WHICH DETECTOR TO CHOOSE?

As can be seen from above, IIs and FPDs both have advantages and disadvantages when used for the needs of electronics inspection. Which one to choose will depend on the required inspection application(s). In the view of the authors, if the need is for fast, live imaging inspection of objects / features containing subtle, low density variations then a high end flat panel detector would be required. An example of this type of application is the inspection during manufacture of Cu-wire inter-connections, which are replacing Au-wire inter-connections, within semiconductor packages. The low image noise and high gray scale sensitivity of the FPD optimises the speed and quality required in the inspection task.

On the other hand, if the inspection application always requires the highest magnification / highest resolution images then an II would be recommended. This is because the detector resolution, the detector gain and the higher available system magnification provides the best imaging from the highest resolution / specification x-ray tubes, when compared to the FPD. However, the imaging task may take a slightly longer time to complete by needing to take more image averages so as to compensate for the higher image noise. Therefore, the II would be recommended for LED production and TSV analysis and inspection, for example, as well as for other failure analysis requirements in Semiconductor manufacture and PCBA, where speed and throughput are less of a priority compared with ultimate imaging resolution.

For all other x-ray applications, such as those typically required for PCBA in-process control & production quality inspection, for example, then <u>BOTH</u> the II and FPD will satisfy the inspection needs. However, a choice will have to be made as to which will be best for a particular location by considering, the price, performance, future inspection needs, etc. that are required and selecting either the II or FPD, as appropriate.

µCT Inspection and Other Factors

A final application area where the FPD may offer a significant advantage over the II is for µCT, or 3D x-ray inspection. This capability is being offered as an option on many high end electronics x-ray systems. The benefit of the FPD here is that its lower image noise means that fewer images need to be averaged / taken during µCT image acquisition than if an II is used. This allows the µCT process to be speeded up and may also improve the final quality of the CT model because of its improved gray scale sensitivity and reduced noise, thereby allowing improved analysis, compared with an II obtained CT model.

This paper has concentrated on the x-ray tube and detector technologies that are in the x-ray inspection systems used today for electronics applications. It has not mentioned other aspects of the inspection system that will make the most of these items for a particular application. For example, consideration must also be given to:

- The ease and speed of sample handling and manipulation
- The capability of the system software functions for the applications analysis required
- Overall ease of use in order to optimise sample throughput and potentially de-skill the inspection task.

All of the above factors must be considered when deciding what is the best system for a particular need. This can only be truly evaluated by inspecting real test samples on the systems that appear to match the required criteria. The true system performance may not always be clearly understood by just looking at system specification sheets.

CONCLUSION

This paper has discussed the various x-ray tube and detector technologies that are available today for the x-ray inspection needs of electronics. It has shown their relative advantages and disadvantages and suggests some system configurations to provide the best inspection for particular applications.

ACKNOWLEDEMENTS

The authors would like to thank Dr. Evstatin Krastev and Bill Walker for their great help with this paper.

REFERENCES

[1] ‘X-ray Tube Selection Criteria for BGA / CSP Inspection’, D. Bernard, Proceedings of SMTAI 2002.

[2] ‘A Practical Guide to X-ray Inspection Criteria & Common Defect Analysis’, D. Bernard & B. Willis, Dage Publications 2006, available through the SMTA bookshop.

[3] ‘Considerations for Minimizing Radiation Doses to Components during X-ray Inspection’, D. Bernard & R. Blish II, Proceedings of SMTAI, 2003.