Considerations for Minimizing Radiation Doses to Components During X-ray Inspection

By David Bernard, Rabans Lane, and Richard C. Blish, II

Abstract

The ability to undertake non-destructive testing on semiconductor devices, during both their manufacture and their subsequent use in printed circuit boards (PCBs), has become ever more important for checking product quality without compromising productivity. The use of x-ray inspection not only provides a potentially non-destructive test but also allows investigation within optically hidden areas, such as the wire bonding within packages and the quality of post solder reflow of area array devices (e.g. BGAs, CSPs and flip chips). During x-ray inspection the sample is bathed in the ionizing radiation of high-energy photons, so the sample receives a radiation dose. Certain devices are susceptible to damage by ionizing radiation. Therefore, this susceptibility may require the user to consider the radiation dose being given to these items during the x-ray inspection process to ensure critical thresholds are not exceeded. This paper will discuss the issues that a user of these radiation-sensitive components may wish to consider, together with practical suggestions as to how to measure and minimize the radiation dose for best practice during x-ray examination

Introduction

Recent articles [1 – 3] have raised the issue of the radiation dose given to components during x-ray inspection. Radiation dose is defined as the amount of energy deposited into unit mass of the material of interest. The units of radiation dose are 1 Gy (Gray) = 1 joule/kg = 100 Rads. The term dose rate is used to indicate the dose per unit time (e.g. Gy/min or Rad/min) that a device will experience at a position from a radiation source, in this case the x-ray source within the x-ray system. Multiplying the dose rate by the time the device spends at that point gives the dose to the device. With very large radiation doses, many orders of magnitude greater than can be achieved during x-ray inspection, a large amount of energy is deposited into the silicon die, for example, and this causes physical damage to the device and therefore its failure. For the manufacturer and user of semiconductor devices, the danger of the radiation dose imparted during x-ray inspection is not this gross failure, where failure is always certain, as these dose levels cannot practically be achieved during shop-floor x-ray inspection. Instead the potential concern is for the subtler failure mechanisms, e.g. bit flips, loss of program and erase margin, leakage, etc., where failure of the device has some statistical, or random, chance of occurring and physical damage is not visible. The difficulty with these random failure mechanisms for commercial-off-the shelf (COTS) products is that their appearance occur at radiation doses that are orders of magnitude less than the 'gross-failure' variety and therefore potentially within the doses given during x-ray inspection.

Considerations for Minimizing Radiation Doses to Components During X-ray Inspection

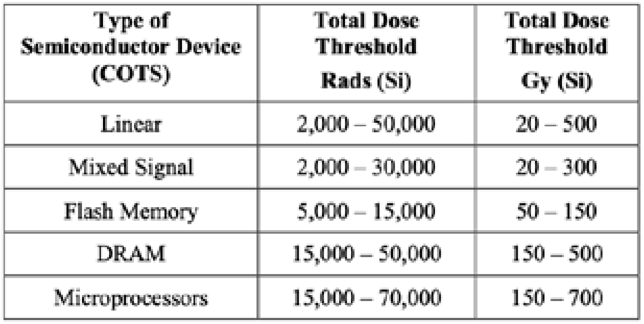
By David Bernard, Rabans Lane, and Richard C. Blish, II

Before concluding that all COTS devices are at threat from x-ray inspection:

- Some devices are more susceptible to radiation dose than others but the vast majority will not be affected by x-ray inspection [4].
- The actual threshold radiation dose levels for the random events are very difficult to define

In fact, the figures quoted in the literature vary by orders of magnitude [see references 1, 4 and Table 1] and therefore may really be far in excess of what can be practically given during even the most extensive x-ray inspection regime to be a problem.

The definition of a random effect means that if the dose threshold is exceeded, subsequent failure is never certain in an individual device on a specific board. Exceeding the dose threshold only increases the probability of a failure(s) occurring within the entire production run (entire population) of that specific COTS device.



Type of Semiconductor Device (COTS)	Total Dose Threshold Rads (Si)	Total Dose Threshold Gy (Si)
Linear	2,000 – 50,000	20 – 500
Mixed Signal	2,000 – 30,000	20 – 300
Flash Memory	5,000 – 15,000	50 – 150
DRAM	15,000 – 50,000	150 – 500
Microprocessors	15,000 – 70,000	150 – 700

Table 1. Approximate Random Total Dose Damage Thresholds for Various Types of Commercial Semiconductor Devices [4].

Should particular device(s) within a board be at potential risk, then the likely dose imparted during the x-ray inspection process will have to be estimated prior to testing.

This requires:

- An understanding, and measurement, of the radiation dose rates that each device is likely to experience within the x-ray system during the various stages of inspection
- Knowledge of the total time spent at each dose rate

In this way, a cumulative dose for each device over the entire inspection procedure can be calculated and matched against the relevant critical threshold. It should also be remembered that radiation dose to semiconductor devices is cumulative [5]. So repeating an inspection regime will double the dose to the device. Repeat inspection, typical after rework, might have, therefore, implications for susceptible devices on a board. It should be noted also that GaAs based devices are much less susceptible to radiation dose damage than Si based devices (reference 1).

Measuring the radiation dose to components, and its subsequent effects, has always been of concern for space/military applications resulting in radiation-hardened devices. These are able to withstand several orders of magnitude more radiation than their COTS equivalents. However, the original impetus for this work was the potential damage to ICs during X-ray inspection of surface mounted devices, especially those suffering cumulative damage from changes to stored charge on internal nodes. The World Trade Centre disaster added at least two new dimensions. The earliest element was a likely increase in the frequency and intensity of airport security screening of cargo and passengers' carry-on or checked baggage. A second element was US Postal Service (USPS) efforts to sterilize mail [6] and parcel shipments to a narrow, selected range of zip codes as an anthrax antidote. USPS dose values are extremely high (5-10 Mega Rads using a 10 MeV electron beam using hundreds of kilowatts!) such that neither commercial devices (see Table 1, taken from [4]), nor even "Rad Hard" devices would survive. Whilst investigating these effects, it was found that there was the potential for a wide variation in the dose imparted to samples from different x-ray inspection suppliers [2,3]. Although the data from different suppliers may have been based on different criteria, as discussed below, this variation raised the question of what users of semiconductor devices should consider such that radiation dose is minimized during inspection.

X-ray inspection systems are basically x-ray shadow micrographs (see figure 1). An x-ray light source (x-ray tube) produces x-rays, which pass through the sample. The differing materials within the sample absorb more, or less, of the x-ray radiation depending on their density and atomic number and cast a shadow of that material at the detector. The denser the material, then the darker the shadow. The closer the sample is moved to the x-ray tube then the larger the shadow becomes and this is how magnification is achieved. The factors that affect the dose given to a sample during inspection are:

- The distance of the sample (device) from the source of the x-rays
- The x-ray tube power used
- The presence of filters (x-ray absorbing material) between the tube and the sample
- Repeat inspections

Considerations for Minimizing Radiation Doses to Components During X-ray Inspection

By David Bernard, Rabans Lane, and Richard C. Blish, II

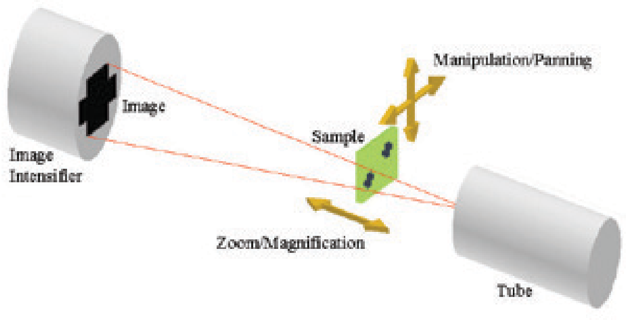


Figure 1: Basic 2-D x-ray system configuration

Dose Rate and Distance

Radiation dose rate varies with the 'inverse square' of distance. In other words, if you double the distance from where you make an initial dose rate measurement, then the dose rate will have decreased by a factor of 4 from the original value. Triple the distance and it will have decreased by a factor of 9, etc. So, how close the susceptible device is to the focal point (source) of the x-rays during the inspection routine will have a dramatic effect on the dose rates, and by extension the doses, that such a device experiences.

A simple prescription, therefore, to minimize dose to samples would be to limit the proximity of the sample with the source. Whilst this offers an excellent opportunity for dose reduction, because devices continue to shrink in size, the need for increased magnification becomes ever more important. So the samples must be moved closer to the x-ray source. Therefore, a compromise between these two issues may have to be made during inspection of specific samples. This is particularly important because of the use of open, or demountable, transmission x-ray tubes as standard within x-ray systems for semiconductor and PCB applications in place of closed x-ray tubes that were more popular a few years ago. The differences between these tube types can be seen in ref 7 but, fundamentally, the design of the open tube offers higher resolution and much greater magnification than the closed tube. The improved magnification is achieved because the sample can be placed much closer to the focal point of the open tube.

As an example, an x-ray system can place a device to within 0.5 mm (or less) of the focal point of an open tube. In comparison, a closed tube has a minimum device to focal point distance of around 15 mm, or more. So, if identical dose rates are assumed to be emanating from the two types of x-ray source, the dose rate at 0.5 mm from the source will be ~ 900 times greater than the dose rate at 15 mm. This is because the longer distance is ~30 times further away than the first position. This is the extreme case. The thickness of the lid of a package will immediately distance the susceptible silicon in the device at least a further 0.5 mm away from the source, resulting in a difference of 210 times between the maximum dose rates possible for open and closed tubes. This ignores the effects of any absorption of the x-rays by the lid material, which would reduce the dose itself. But as the packaging material is usually made of low-density material, there will be little attenuation in reality and the effect on dose can be ignored this purpose. Once the thickness of the sample holder, a typical feature of x-ray systems, is added to the separation distance (~1.0 mm) from the tube focal point, the difference in the maximum dose rates from the two tube types decreases to around 50 times. This last figure is probably a more realistic upper value that typical inspection using open tubes might experience compared to closed tubes. However, it still means that the device, although being inspected at the much higher magnification, will reach a threshold dose 50 times quicker at the closer distance. The difference in using open and closed tubes may have been one of the reasons for the variation in the dose rates achievable by different x-ray systems in ref [2,3].

The above assumes that the most susceptible component is placed as close as possible to the focal point of the x-ray and that the entire device is being irradiated in a uniform field. Once the geometry of the device is considered, then certain parts of the device will, in reality, be further away from the source and so experience a dramatically lower dose. So calculating the true dose to a device will need to take into account which locations are inspected at the maximum available magnification instead of necessarily assuming that the whole device always sees the maximum dose rate. This will reduce the total dose to a device during inspection. However, it should also be remembered that if the device is on a board, or tray of similar components, then the total dose will also have to include the total time that the device spends in the radiation field whilst other devices are inspected. This might be significant, even though the device is relatively distant from the source.

Apart from the radiation dose rate varying with the 'inverse square' of distance described above, it also varies linearly with the cosine of the angle of incidence of the x-ray beam with the sample. Therefore, if the sample is tilted from normal in the x-ray beam, so as to produce oblique views at the detector, there will be a reduction in the dose rate seen by the device, and so reduce the dose/risk during inspection. This can be an important consideration because taking oblique x-ray views is very important, particularly for investigating BGAs and other area array devices. This is because the shape of the solder ball obscures examination of the joint interfaces if only imaged from directly above (i.e. with normal x-ray incidence). Using oblique views overcomes this limitation and helps with the identification of opens following the reflow process during manufacture. By tilting the sample, technically there should also be a consideration that the susceptible item, e.g. silicon die, will experience a variable dose rate across the length that moves away from the source and raises questions as to if parts of the die more at risk than others. For simplicity, however, it is suggested that the maximum dose rate experienced, from the point of closest distance to the source, should be used so as to err on the side of caution during dose calculation.

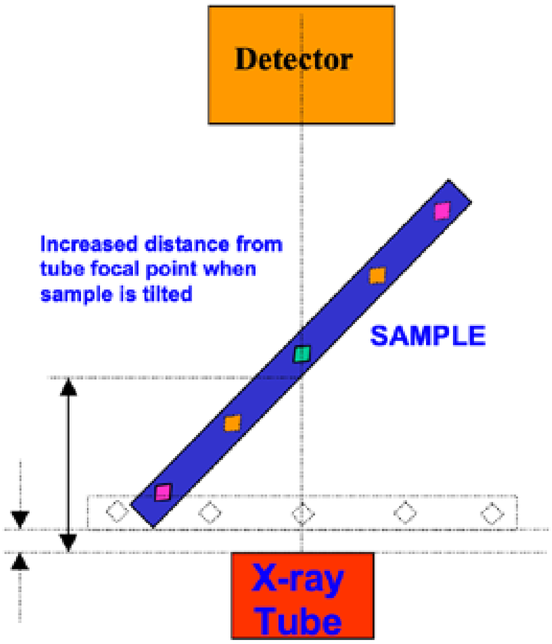


Figure 2: Tilting the sample moves it away from the x-ray tube so as to prevent any collision with the tube. This increases the sample distance from the tube focal spot and so dramatically reduces the available magnification

Any possible reduction in dose rate from having an angled x-ray beam may also have to be ignored because x-ray inspection systems have evolved over recent years. This has centred on the need to provide oblique views at higher magnifications owing to continued shrinkage of device size.

The older method of tilting the sample to provide the angled view requires the sample be moved away from the tube focal point to prevent in-system collisions and, therefore, reduces the magnification. Today, x-ray equipment manufacturers prefer to keep the sample perpendicular to the focal point at all times and achieves oblique views by moving the detector (see figures 2 and 3). In this way, the need for oblique views does not compromise the available magnification and potentially limit analytical detail. However, this means there is no net dose rate reduction from having an angled beam at a larger distance on the device so dose estimates must be adjusted accordingly.

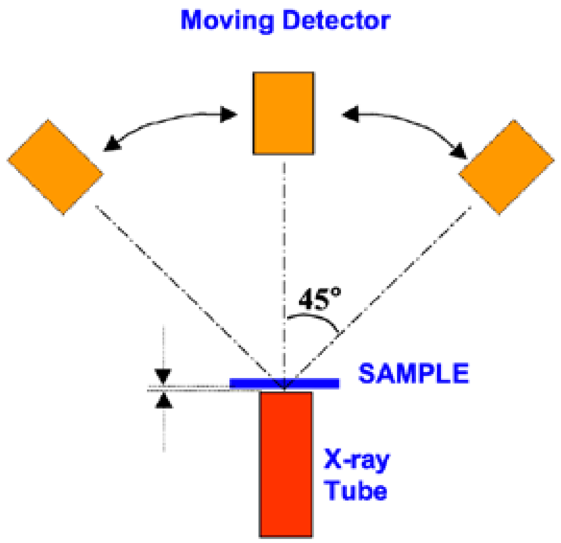


Figure 3: By moving the detector to make oblique angled views, the sample remains horizontal at all times so there is no compromise to the available magnification when an angled view is required.

Dose Rate and Tube Power

The dose rate from the x-ray tube is also affected by the power of the tube. The power is calculated from the product of the accelerating potential used to make the electron strike the target (called the kV) and the filament current that produces the electrons. The kV is also a measure of the penetrating power of the x-rays. The higher the kV used then the more penetrating are the resultant x-rays. These parameters are used to set the tube at appropriate levels so as to get a good contrast image at the detector. To a reasonable approximation, the dose rate is linear with power and so as the power doubles, so does the dose rate, for example. The more power then the brighter the source. However, there are technical limitations on the maximum power that the tubes can achieve (see ref [7]) but the greater the power used then the less time there is for inspection before a critical threshold is reached. As mentioned above, whatever tube conditions are used, and these may vary within an inspection regime depending on the device type and the nature of the inspection required, repeating the inspection routine will double the dose to the device.

Dose Rate and X-ray Beam Filtration

The technique of x-ray inspection demands that the incident x-ray beam is absorbed at various degrees by different density materials in the device/board before being detected. Apart from attenuating the strength of the x-ray beam by passing through

Considerations for Minimizing Radiation Doses to Components During X-ray Inspection

By David Bernard, Rabans Lane, and Richard C. Blish, II

material, there is also a modification to the x-ray energy spectrum. This effect can be used to reduce the dose to devices substantially. For example, the PCB board material or the packaging material of a device can ‘protect’ the susceptible silicon by filtering the x-ray beam. The deliberate use of additional filtration, through placing some thickness of material immediately in front of the sample, can also improve the detection sensitivity [3]. This is achieved by optimising the contrast of certain materials in the sample, such as the copper used as tracks in the PCB and the Sn/Pb solder (or Pb-free variants) used for the joints, without increasing dose to silicon. By using appropriate filters, the dose to susceptible components can be dramatically reduced without compromising the image quality needed for analytical determination. References 2 and 3 show that an optimal filter for x-ray inspection, which functions as a high pass (energy) filter, should ideally have an atomic number in the range Z = 30 – 35, that is a few greater than Cu (Z = 29). With the susceptible component within the devices being typically silicon (Z = 14) references 2 and 3 indicate that zinc (Zn) has the best properties for semiconductor and PCB applications. This is because its x-ray absorption profile blocks the low energy X-rays that add to dose in silicon without improving image quality and therefore will protect the silicon. Meanwhile, the copper tracks and tin/lead (or lead-free) solders (Sn Z = 50 and Pb Z = 82) within the PCB are still imaged well by higher energy X-rays typically available within x-ray inspection systems.

Reference 3 indicates that a thickness of around 300 – 400µm of zinc foil will provide full protection for the most susceptible devices. In practical terms, however, this substantially reduces the x-ray flux passing through the sample, producing low contrast images and requiring long acquisition times. Instead, a compromise of ~ 100 – 150µm thickness of zinc as the filter is proposed. This will reduce the dose to the susceptible silicon by a factor ~ 100 X [3] but the change in brightness and contrast in the x-ray images produced is much more modest and can be easily handled by today’s x-ray imaging systems to still give useful analytical images.

Estimating/Calculating Doses During X-ray Inspection

There are many different designs and specifications of open and closed x-ray tubes available, in different system configurations, in the market. As such, there is a wide variation in the closest proximity the sample can be placed in relation to a particular tube focal point, the most important factor affecting the dose given to a sample.

X-ray system manufacturers should be able to provide data on their systems that will indicate the change of dose rate with linear distance from the tube focal point, at various tube power values, for their specific systems. It is then possible to estimate the dose to devices during inspection using these values in conjunction with:

- Knowing of the distance susceptible components will be from the tube focal point at each stage in the inspection procedure.
- Applying suitable correction values to adjust the manufacturer dose rates to be appropriate for the kV used at each stage in the inspection procedure.
- Estimating the time spent at these conditions for each stage of the inspection routine.
- Adjusting the dose rates accordingly should additional filters be deliberately used to modify the x-ray beam.

By summing the dose component at each inspection step, a total dose to a device can be calculated. This will ignore the effect of additional filtration from the PCB board or packaging material, for example, but will provide a reasonable upper limit to the dose expected during examination. This can then be compared to the critical thresholds for the device. To corroborate this data, it is recommended that specific measurements be taken on a simulated board. Unfortunately, measuring radiation cannot be done directly. All radiation measurement requires a perturbation of some natural function within a measurement medium, which can then be detected and calibrated against known reference values. For example, the radiation can ionize the gas (air) in a chamber volume and the amount of ionization can be measured as a charge or current and calibrated against known doses/dose rates. However, the values generated are specific for the measurement medium used. Conversion factors are necessary, therefore, to convert the dose measured in one medium (e.g. Air) into the dose in a second medium (e.g. Si). These conversion factors are readily available (ref?) but they are generally energy dependent. So when a regime is decided upon to measure the dose given during x-ray inspection (e.g. use of TLDs), the results of those measurements must be converted into dose to the susceptible material (silicon in the case of semiconductor devices).

Overall, the best approach is to run tests using simulated boards/components and make measurements using Thermo-Luminescent Detectors (TLDs), for example. TLDs are a useful dosimeter choice, as they are simple to use and good for measuring integrated dose applications. Their principle of operation is to create “color centers” within their crystal structure when ionizing radiation, the x-rays in our case, are absorbed. Subsequent heating of the TLD material releases the stored photons created by the radiation, as each color center is driven back to its lowest energy state. These photons can be captured and counted, for example, by using a photo-multiplier tube. The results (photons = dose) from the test sample can

Considerations for Minimizing Radiation Doses to Components During X-ray Inspection

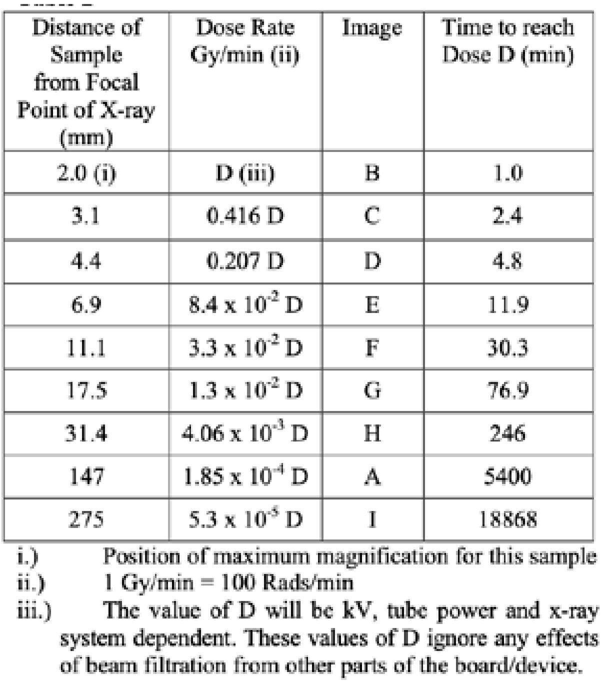
By David Bernard, Rabans Lane, and Richard C. Blish, II

then be referenced against a calibration table for the TLDs used. Irradiating the TLDs, and subsequently reading them, with known radiation doses produces the calibration table. Lithium Fluoride (LiF) and lithium borate are the most commonly available TLD materials and are appropriate for PCB and semiconductor applications. LiF TLDs are linear in their dose to light response to 10 Gy; whereas lithium borate TLDs are still useable, and linear, up to 1000 Gy.

Methods for Dose Minimisation

The following steps should be considered singly, and in combination, to minimise the dose imparted during x-ray inspection.

- Increase the distance between the sample and the tube focal point. The following example of a flip chip on a dummy Bluetooth board shows how the dose rate at the sample for that magnification varies as the distance between the sample and the tube focal point increases (see images A – I and table 2). The available magnification is decreased but not to a detrimental amount for analysis to take place. However, the dose rates that the sample sees are dramatically reduced and so permit a much longer time for inspection if it is needed.
- Place additional filtration between the sample and the x-ray source. A value of ~ 100 – 150 microns of zinc is suggested. This will reduce the dose by a factor of ~ 100 X, or allow 100 X the inspection time, if needed, without compromising too greatly the image quality. See images J and K for an example.
- Minimise the time for inspection by automating the procedure as much as possible so that only those areas that need examining are investigated.
- Consider the necessity of subsequent or repeat inspections, such as after rework. Are they necessary?
- Make corroborative dose measurements with TLDs to validate your understanding of your x-ray system and confirm the doses that you are likely to give to the samples.



Distance of Sample from Focal Point of X-ray (mm)	Dose Rate Gy/min (ii)	Image	Time to reach Dose D (min)
2.0 (i)	D (iii)	B	1.0
3.1	0.416 D	C	2.4
4.4	0.207 D	D	4.8
6.9	8.4×10^{-2} D	E	11.9
11.1	3.3×10^{-2} D	F	30.3
17.5	1.3×10^{-2} D	G	76.9
31.4	4.06×10^{-3} D	H	246
147	1.85×10^{-4} D	A	5400
275	5.3×10^{-5} D	I	18868

i.) Position of maximum magnification for this sample
ii.) 1 Gy/min = 100 Rads/min
iii.) The value of D will be kV, tube power and x-ray system dependent. These values of D ignore any effects of beam filtration from other parts of the board/device.

Table 2 and the images A – I show how changing the PCB to focal point distance affects the dose rate that this sample receives, and what influence this change of distance has on the magnification of the final x-ray image. For example, if image E were used for inspection purposes, instead of image B, the analytical information is hardly compromised but the dose rate at the sample is reduced to less than 90% of that at image B. Looking at the situation in another way, the operator could spend nearly 12 times longer inspecting at the image E position compared to image B.

In this example, the PCB was sitting on a 1 mm thick aluminium sample plate and the open, transmissive, x-ray tube used in the system had a beryllium window thickness of 0.5 mm. The position of maximum magnification is shown as 2.0 mm because the thickness of the board has also been included (0.5 mm) in the separation distance. The writing seen in images A and F – I is on the reverse side of the board to the devices.

Considerations for Minimizing Radiation Doses to Components During X-ray Inspection

By David Bernard, Rabans Lane, and Richard C. Blish, II

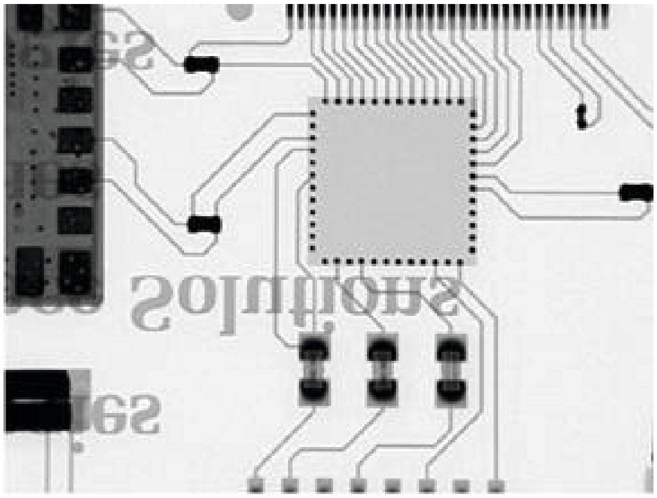


Image A: Flip chip on dummy Bluetooth board. Sample 145 mm from position of highest magnification. Red circle indicates magnified area in subsequent images. Sample on 1 mm Al sample tray for all images A – I. Dose rate ~ D/5400 Gy/min

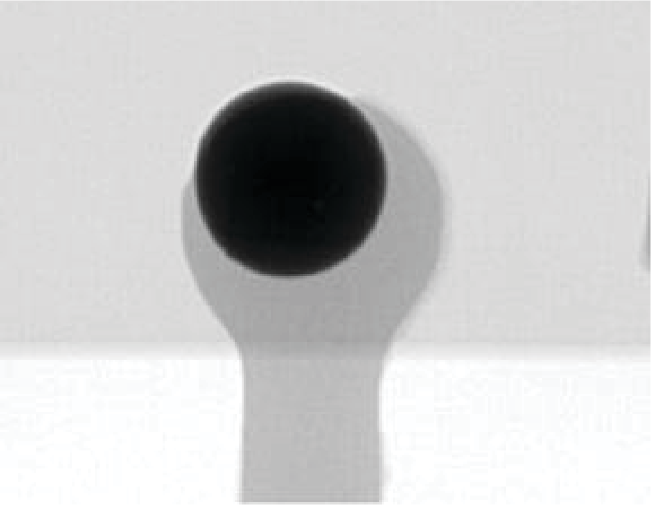


Image B: Sample at position of highest magnification and so receiving highest dose rate – D Gy/min. Solder ball ~ 190µm diameter.

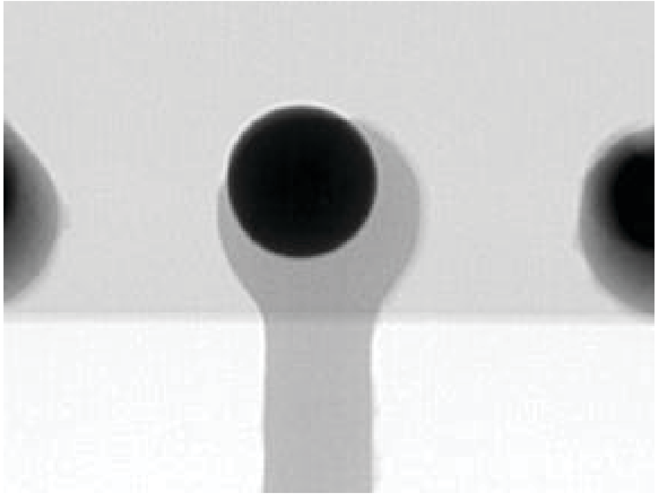


Image C: Sample 1.1 mm away from position of highest magnification. Dose rate ~ 0.4D Gy/min

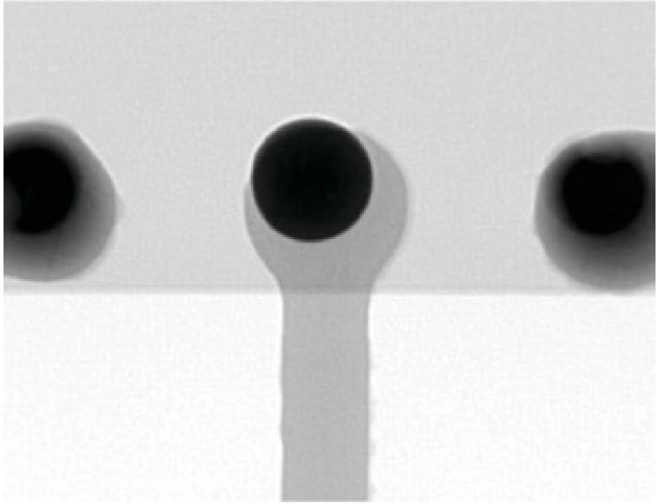


Image D: Sample 2.4 mm away from position of highest magnification. Dose rate ~ D/5 Gy/min

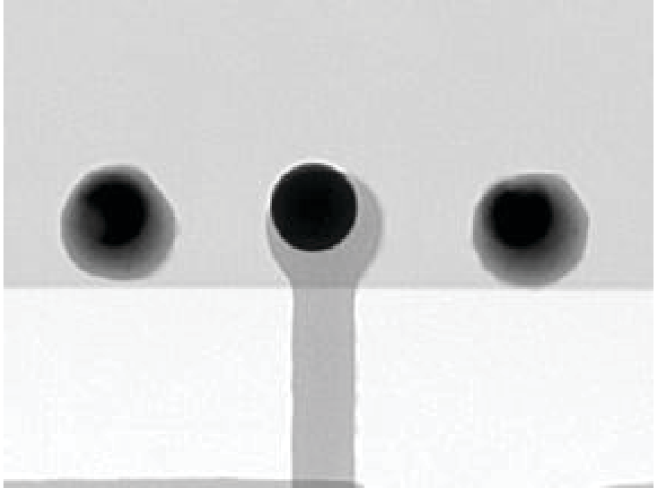


Image E: Sample 4.9 mm away from position of highest magnification. Dose rate ~ D/12 Gy/min

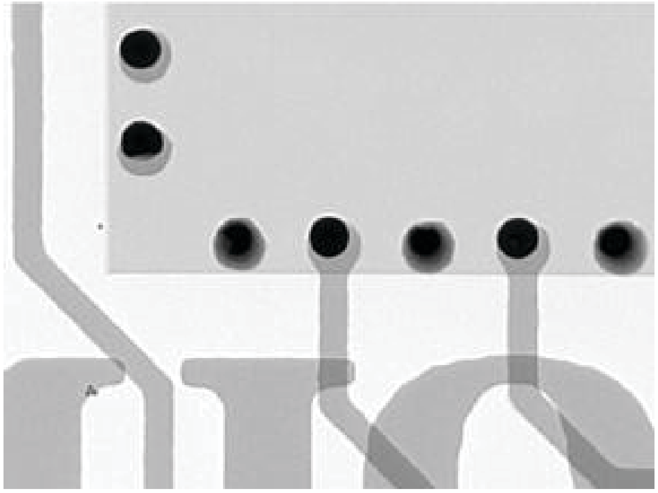


Image G: Sample 15.5 mm away from position of highest magnification. Dose rate ~ D/77 Gy/min

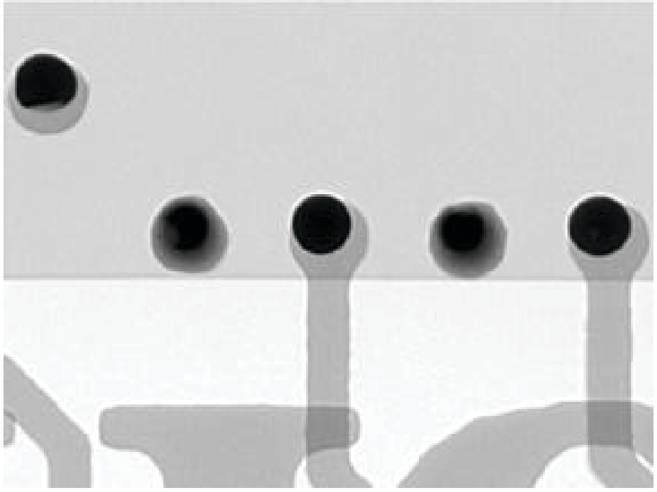


Image F: Sample 9.1 mm away from position of highest magnification. Dose rate ~ D/31 Gy/min

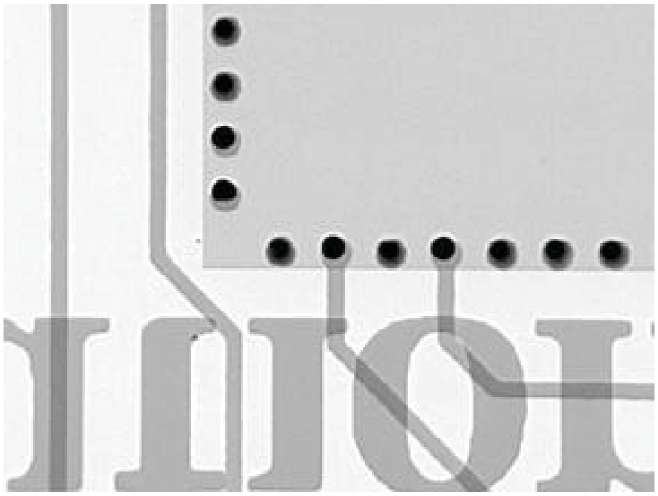


Image H: Sample 29.4 mm away from position of highest magnification. Dose rate ~ D/247 Gy/min

Considerations for Minimizing Radiation Doses to Components During X-ray Inspection

By David Bernard, Rabans Lane, and Richard C. Blish, II

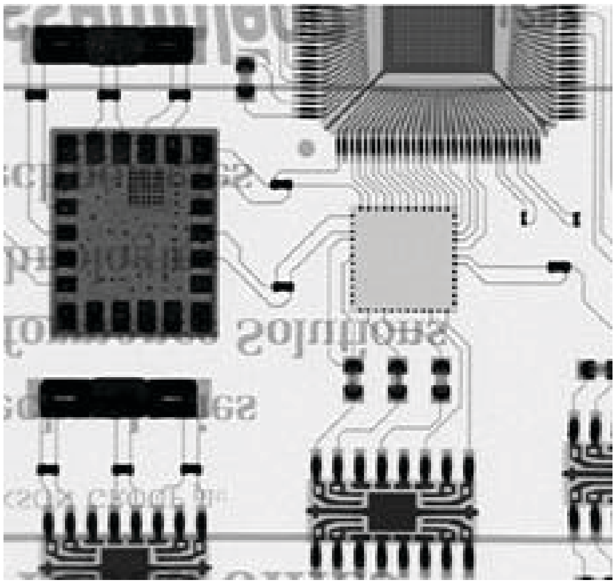


Image I: Sample 273 mm away from position of highest magnification. Dose rate ~ D/18906 Gy/min.

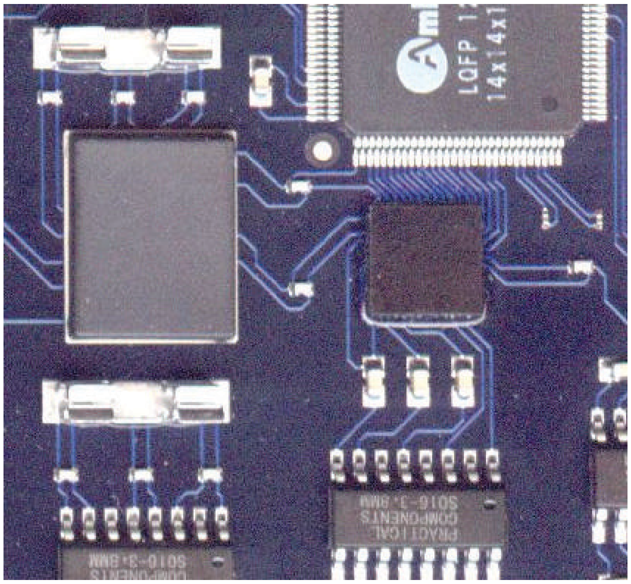


Image I Optical: An optical image of the same board highlighting the features that are visible under x-ray inspection that are not seen optically.

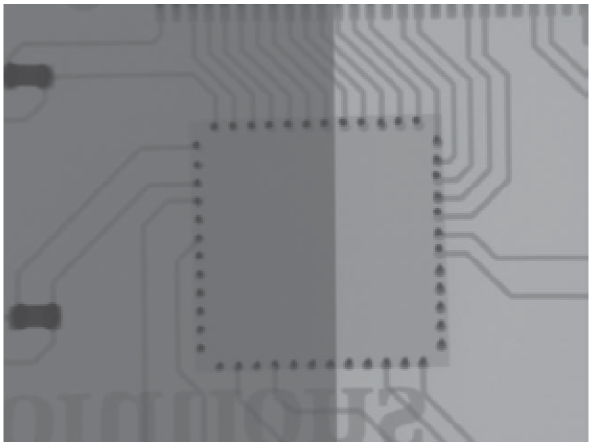


Image J: Image of flip chip with 100 µm thick zinc foil under the left half of the device.

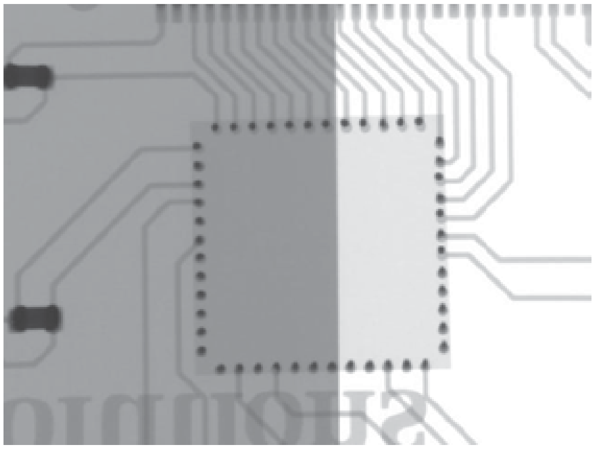


Image K: Image J after contrast adjustment has been applied by the x-ray system operating software. The filtered portion of the image can clearly be used for analytical purposes.

Considerations for Minimizing Radiation Doses to Components During X-ray Inspection

By David Bernard, Rabans Lane, and Richard C. Blish, II

Conclusions

The radiation doses given to electronic devices during x-ray inspection may be higher than expected because of need for inspection at higher magnification. This brings the susceptible part of the device (usually the silicon die) closer to the source and so exposes the device to greater dose rates. Therefore, it may be necessary to question if any of the devices being inspected are susceptible to random radiation damage at the dose levels that are planned for inspection. If this is the case, then it is necessary to estimate and, if possible, corroborate with measurements, the doses delivered during the proposed inspection regime. If the radiation dose to be delivered is likely to be at a level that is cause for concern then certain actions can be taken to reduce the imparted dose. These actions include that can be applied singly or in combination are:

- Wherever possible, cut down re-inspection, as dose is cumulative
- Deliberately place the sample further away from the tube focal point. This decreases the available magnification but will dramatically reduce the dose rate during analysis.
- Apply additional filtration of ~ 100 – 150 µm thickness of zinc foil.

REFERENCES

- T. Clifford, Electronic Packaging and Production, 02/01/2002
- R. Blish IEEE International Reliability Physics Symposium, Dallas, TX, April 2002
- R. Blish et al. IEEE Trans. Devices & Materials Reliability, Vol. 2, #4, pp 102-106 (2002)
- http://nppp.jpl.nasa.gov/docs/Radcrs_Final5.pdf, from which the final two pages provide total dose thresholds for commercial semiconductor devices and citations
- P. V. Dressendorfer, Basic Mechanisms for the New Millennium, IEEE Press, NSREC Short Course, 1998
- http://www.usps.com/news/2001/press/pr01_093.htm, describes USPS plans.
- D. Bernard, The Proceedings of SMTA International Conference, September 2002

For more information, speak with your Nordson representative or contact your
Nordson Test & Inspection regional office

Europe, SEA, Africa
ti-sales-eu@nordson.com

China
ti-sales-cn@nordson.com

Singapore
ti-sales-eu@nordson.com

Korea
ti-sales-korea@nordson.com

Americas
ti-sales-us@nordson.com

Japan
ti-sales-jp@nordson.com

Taiwan
ti-sales-tw@nordson.com

www.nordson.com/TestInspect | +1 760.918.8471

Copyright © Nordson Corporation. All rights reserved.

Nordson
Test & Inspection