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TDI Imaging: An Efficient AOI and AXI Tool

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Abstract
As a result of heightened requirements for quality, integrity and reliability of electronic products, the role of wafer auditing and nondestructive testing of printed circuit boards and electronic assemblies has grown at an unprecedented rate. Nondestructive testing improves a product's performance, increases quality and reliability, and lowers return rate. It is estimated that the cost of a failure decreases by a factor of ten when the error is identified in the course of production instead of in the field. Optical and x-ray cameras have become the most efficient and reliable tools for nondestructive testing.

Time delay integration (TDI) method of imaging is based on the concept of accumulation of multiple exposures of the same object. The primary advantage of this method compared to the conventional line-scan method is the possibility of detecting low exposure levels with a superior signal-to-noise ratio when high spatial resolution is required.

In the semiconductor industry, TDI-based instruments are used for wafer and reticle inspections where ultraviolet (UV) and deep ultraviolet (DUV) instruments are mandated by defect detection requirements. In the electronics industry, TDI-based instruments can be efficiently used for high-speed automated optical inspection (AOI) of high-density electronic assemblies where dimensions of components populated on the PCB (printed circuit board) become smaller, and spacing between the components becomes narrower.

X-ray TDI cameras are a critical part of the automated x-ray inspection (AXI) systems used for inspection of multilayer printed circuit boards and circuit card assemblies with BGA (ball grid array) and other SMT (surface-mount technology) components. High-resolution x-ray TDI cameras allow efficient inspection of the printed pattern, wire bonding, quality of soldering of BGA components, and other elements of a PCB structure and circuit assembly.

Introduction
While charge-coupled devices (CCD) and complimentary metal-oxide-semiconductor (CMOS) image sensors remain the imagers of choice for traditional imaging applications such as high-fidelity image capture and spectroscopy, time delay integration technology has changed the way we image moving objects or detect low exposure levels. The TDI method is based on the concept of noiseless accumulation of multiple exposures of the same object. The primary advantage of this method is greatly increased integration time, which allows collection of more photons.

Since the mid-1970s, many publications have documented development of TDI-CCD imagers for applications in military reconnaissance and satellite imaging. Performance of those early systems was limited by the insufficient size and low resolution of the imagers. Recently, there has been a wave of renewed interest in the use of TDI technology for semiconductor and PCB inspection, counterfeit detection, document scanning, biomedical, astronomical, and other industrial and scientific applications.

Advances in TDI technology, in combination with advances in x-ray technology, have made x-ray TDI cameras one of the most efficient methods of nondestructive inspection in the electronic industry. These cameras enable visual detection of defects beneath opaque components, in multi-layer PCBs, electronic assemblies, and finished electronic products.

Compared to more mature nondestructive testing (NDT) methods, TDI high-sensitivity AOI and AXI systems significantly improve spatial resolution while providing high signal-to-noise ratio and throughput of the inspection systems.

CCD Image Sensor: Essential Element of TDI Imagers
A CCD image sensor consists of an array of photosensitive charge-coupled elements (pixels). The output signal of the sensor is proportional to the electrical charge accumulated by each pixel in response to its irradiation. Charge transport in a charge-coupled imager is controlled by multiphase (usually two to four) clock signals, which induce potential wells under the electrodes and control motion of the electron packages residing in the potential wells. Charge transport includes transferring charge packets in the columnar direction, as well as clocking off the charge through the horizontal (readout) register to the

charge-measurement circuit and output amplifier. This procedure causes charge packets to exit the array of pixels one row at a time.

The effective readout rate of a CCD sensor can be improved by a multiport (or multitap) architecture. However, this architecture requires that the output circuits used for each tap have well-matched characteristics; otherwise, the part of the image serviced by one amplifier may have a contrast different from the remaining image serviced by other amplifiers.

Among known architectural configurations of CCD imagers, three of the most popular are called full frame, frame transfer, and interline. The full-frame architecture, which provides a 100% fill factor, is the most universal CCD architecture used for traditional scientific and industrial applications, as well as for TDI applications.

Quantum efficiency (QE) is a measure of how well a specific sensor responds to different wavelengths of light. The higher the QE, the more sensitive a CCD will be at a particular wavelength. Spectral response is a CCD characteristic that represents the relation between QE and wavelength. Depending on a required spectral response, CCD sensors can be designed for front or back illumination.

In front-illuminated CCDs, light must pass through a polysilicon gate structure located above a photosensitive silicon layer called the "depletion layer." However, variations in the refraction indices between the polysilicon and the silicon cause shorter-wavelength light to reflect off the CCD surface. This effect, combined with intense UV light absorption in polysilicon, leads to diminished QE for those wavelengths in the front-illuminated detectors.

To improve the overall QE and enable increased CCD sensitivity at UV and DUV wavelengths, back-thinned technology can be used.[1] In back-thinned devices, also known as back-illuminated CCDs, the incident photon flux does not have to penetrate the polysilicon gates and is absorbed directly into the silicon structure. As the semiconductor industry moves toward smaller design rules, applications for these wavelengths are also gaining greater importance, and the spectral response characteristics of back-thinned versus front-illuminated CCD devices become critical. Spectral response characteristics differ significantly for back-thinned and front-illuminated CCD sensors (see Fig. 1).

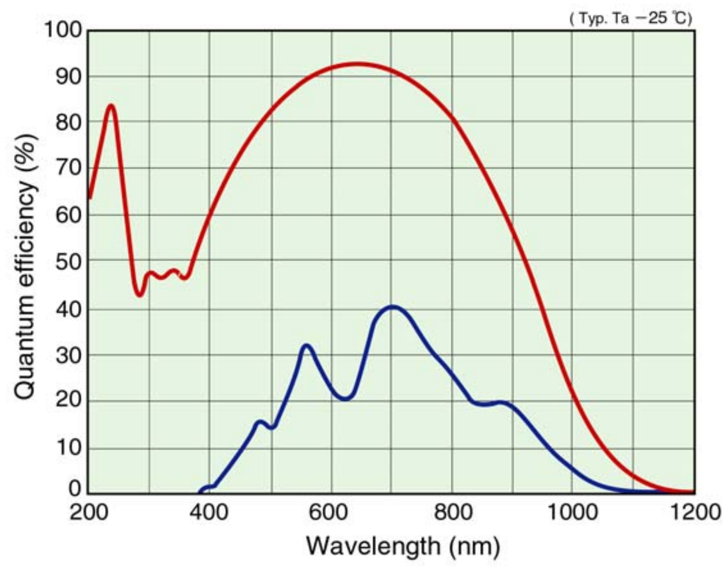

Figure 1: Spectral response characteristics of back-thinned (red) and front-illuminated (blue) CCD sensors

TDI Concepts and Instruments

Time delay integration CCD technology is used for applications with relatively fast movement between the camera and the object being captured. Because integration time increases proportionally with the number of TDI stages, TDI technology is also used for detecting low-light levels where increased integration time is required.

In traditional CCD applications, the charge is accumulated in the charge-coupled elements during the exposure (integration) period. Then, during the readout period, the charge is clocked off the pixels. A signal charge is transferred from one potential well to another toward the output amplifier as a packet, without getting mixed with charges accumulated in other potential wells. In the TDI mode, the same object is imaged multiple times (see Fig. 2). As the image moves from one row of CCD pixels to the next, the generated charge moves along with it, noiselessly integrating with the previously generated charge. This provides a higher sensitivity at low light levels than can be achieved with a traditional line scan camera.

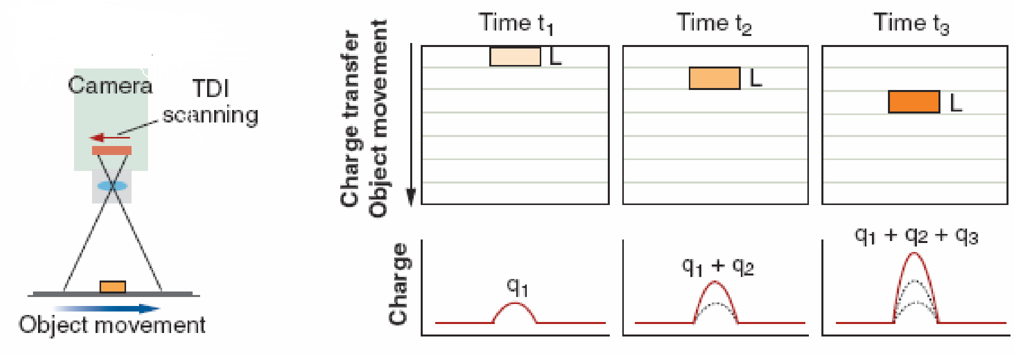

Figure 2: General principle of TDI operation

Consider time point t_1 at which the image of line L of the object to be imaged is focused on the first row of the CCD pixels. Charge q_1 corresponding to the light intensity of line L is collected in the first row of pixels during the scanning of this line. At time point t_2, the image of line L will be captured by the second row of pixels, thus generating in this row charge q_2 corresponding to the light intensity of L. This newly generated charge is integrated with charge q_1 collected at time t_1 and shifted from the first row of pixels. The integrated charge is equal to $q_1 + q_2$. At the same time, the image of the next line of the object will be focused on the first row of CCD pixels (not shown).

The image intensity of line L increases as newly generated charges are added to the existing ones. This operation will continue until the TDI scanning sequence is complete, and the integrated charge that represents line L is clocked off to the horizontal readout register. Then this integrated signal is quickly - within the scan time of one line - shifted off to the output amplifier. Fig. 3 illustrates the process of signal integration in the TDI system.

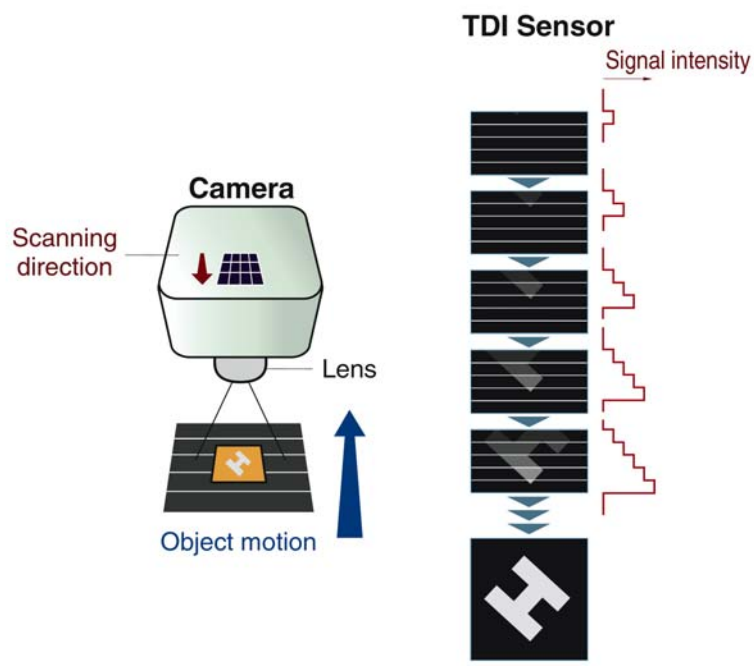

Figure 3: Signal integration in the TDI system

TDI technology requires precise synchronization between vertical shift (scan) frequency in the TDI-CCD and the conveyor speed. If the scan rate of the detector is matched with the velocity of the moving object being imaged, the image will not blur. Suppose the speed of the moving object is V (m/s) and the pixel size is d_2 (µm). If an element on a moving object to be imaged by a single CCD pixel has a dimension of d_1 (µm), the magnification ratio will be $M = d_2/d_1$. In this case, the vertical shift (scan) frequency of the TDI sensor in MHz should be:

$$f = \frac{V}{d_1} = \frac{V \times M}{d_2}$$

For the N-stage TDI-CCD imager, where N is the number of CCD rows, the TDI integration time will be N times longer than the exposure time of one line. Therefore, the signal charge collected for the duration of the vertical shift will also increase by factor N. Accordingly, shot noise will increase by the square root of N, resulting in a theoretical signal-to-noise ratio improvement of the square root of N as well.[2]

The practical limit on the number of TDI stages is determined by the accuracy of synchronization between the vertical-shift frequency and the velocity of the moving object (see Fig. 4).

Figure 4: Scan-velocity mismatch

An image collected with a TDI-CCD sensor is impacted by the effect of scan-velocity mismatch.[3] When the TDI scan rate is precisely synchronized with the velocity of the object, no image artifact is observed (a). When the TDI scan rate is 10% higher, a slight image elongation is observed (b). Conversely, when the scan rate is 10% lower, a slight image compression is observed (c). If the TDI scan rate is deliberately made about 30% lower than velocity of the object, image degradation becomes substantial (d). A Hamamatsu camera series C10000 with a 128-stage TDI-CCD sensor was used for these experiments.

Modulation transfer function (MTF) can also be affected by scan-velocity mismatch and by angular misalignment of the TDI-CCD registers (pixel rows) with the direction of scan [4]:

$$MTF_{vel} = \frac{\sin\left[\frac{\pi}{2} \cdot \frac{\Delta V}{V} \cdot N \cdot \frac{f_{sig}}{f_N}\right]}{\frac{\pi}{2} \cdot \frac{\Delta V}{V} \cdot N \cdot \frac{f_{sig}}{f_N}}$$

$$MTF_{ang} = \frac{\sin\left[\frac{\pi}{2} \cdot N \cdot \tan\Phi \cdot \frac{f_{sig}}{f_N}\right]}{\frac{\pi}{2} \cdot N \cdot \tan\Phi \cdot \frac{f_{sig}}{f_N}}$$

wherein $\Delta V/V$ is velocity mismatch,
N is number of TDI stages,
f_{sig} / f_N is normalized spatial frequency, and
Φ is angular misalignment.

It has been reported that a 2% to 4% scan-velocity mismatch is acceptable for 96-stage TDI devices used for semiconductor inspection.

As the speed increases and available light decreases, design requirements such as imager size, pixel size, spectral response, number of TDI stages, pixel rate, and readout noise become increasingly important. A new generation of back-thinned TDI-CCD sensors and camera-level products recently developed by Hamamatsu addresses most of these design needs. The 2 x 16-tap sensors (see Fig. 5), which have 4096 x 128 active pixels (12µm x 12µm) and a bidirectional charge-transfer capability, provide a TDI scan rate up to 100 KHz.

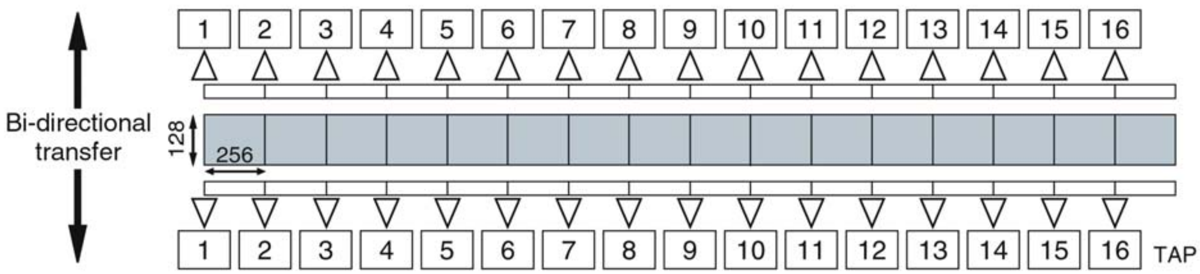

Figure 5: Multitap TDI sensor for bidirectional scanning

The TDI-CCD cameras which utilize these sensors are useful for high-speed bidirectional scanning operations where high sensitivity and low noise are desired.

X-ray Line Scan and TDI Cameras

A typical x-ray inspection system consists of an x-ray source and a camera placed opposite each other, both usually enclosed within an x-ray cabinet for safety. To capture x-ray images, an object is placed between the source and camera. X-rays from the x-ray source penetrate the object and project an image onto the camera.

The sharpness of the image is influenced by the x-ray source: the smaller the focal spot of the source, the sharper the received image. For high-resolution applications such as AXI of printed circuit boards, a microfocus x-ray source provides better resolution.

There are generally two types of x-ray inspection systems: standalone x-ray systems which are used for off-line inspection and x-ray systems integrated into the production line, which are used for in-line inspection. An off-line inspection system is usually used for testing of PCB samples from a batch. In contrast, an in-line inspection system is used when inspection of every product on the production line is required. The type of inspection system (off-line or in-line) and the production volume dictate the appropriate type of x-ray camera to be used.

For off-line inspection systems, x-ray cameras with 2-D image sensors are generally used. These cameras usually employ a 2-D image sensor, such as a CCD or CMOS imager, coupled to a scintillator. The scintillator converts x-rays into visible light that the CCD or CMOS sensor detects. For in-line inspection systems, a 2-D camera can be used if throughput is not a critical factor. The throughput capability of a 2-D camera can be affected by the size of the objects to be imaged. Small objects whose images can be projected entirely onto the image sensor are imaged in one shot (exposure). However, large objects with a significantly asymmetric aspect ratio (width vs. length) require multiple exposures as it is difficult to project the entire image onto the image sensor and still retain sufficient resolution. Because of this, a stop-and-go process required to image large objects takes a long time. In the stop-and-go process, the conveyor stops while one portion of the object is imaged, then moves forward, then stops again for another portion of the object to be imaged. The time needed for each step in the stop-and-go process lowers the system's throughput.

If high throughput is critical for in-line inspection, then a line scan camera is needed. An x-ray line scan camera's major component is a linear detector coupled to a scintillator. Line scan cameras usually utilize linear diode array (LDA), CCD or

CMOS detector technology. Line scan cameras are simple to operate and integrate into a higher level inspection system. Their slim design allows installation of these cameras in a production line, underneath a conveyor belt (see Fig. 6).

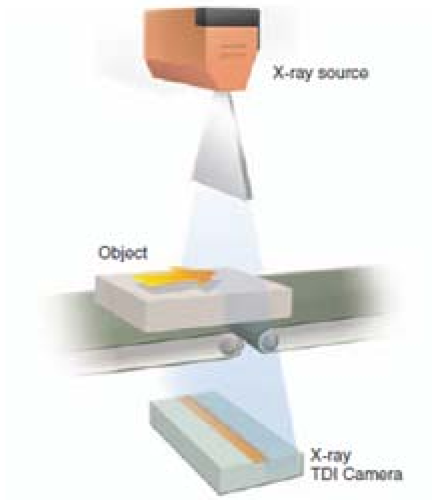

Figure 6: Exemplary configuration of an in-line x-ray inspection system

These cameras capture images of objects on a conveyor by scanning the objects one line at a time as the conveyor moves. The lines are then stitched together by computer software to reconstruct the object's entire image. The line scan cameras require less radiation compared to a 2-D camera. The line sensor requires only a narrow beam of x-ray irradiation compared to 2-D cameras, which have a much larger area to be exposed. The reduced amount of radiation requires a simplified design and reduced space for the x-ray enclosure. Line scan cameras provide sufficient resolution for many inspection applications in the electronic industry. However there is a limit to spatial resolution – these cameras typically have pixel sizes greater than 0.1 mm.

An efficient AXI method which allows obtaining a higher resolution without compromising sensitivity is the method of x-ray TDI imaging. The x-ray TDI cameras provide sufficient resolution and sensitivity to inspect multilayer printed circuit boards, electronic assemblies with BGA and other surface-mounted components. They can detect solder bridges, open solder joints, insufficient or excess solder, voids, misregistrations, missing components, and other defects. These systems also allow visualizing the internal structure of electronic components, including the dies, wire bonds and other elements, and distinguishing the authentic components from counterfeit components.

The Hamamatsu x-ray TDI camera (see Fig. 7) provides 292 mm detection width, scanning rate up to 2.1 KHz and 16 bit ADC (analog-to-digital conversion) resolution. This "no-gap" camera includes a TDI-CCD sensor with 48µm x 48µm pixels coupled to a fiber-optic plate with scintillator (FOS). The camera also includes analog and digital signal processing circuits, data output and control interfaces, and other electronic circuits. It can work with x-ray sources ranging from 25 kVp to 85 kVp.

Figure 7: Hamamatsu x-ray TDI camera

AOI and AXI Applications

The more effective integration time provided by TDI-CCD sensors makes them suitable for numerous AOI and AXI applications.

In the semiconductor industry, manufacturers require wafer-auditing systems that can measure results of the layering, patterning, and doping processes for each layer. Time delay integration devices with gigapixel-per-second data rates have been used for wafer and reticle inspections in the semiconductor industry, wherein UV and DUV instruments must comply with defect detection requirements in deep-submicron microelectronics technologies.[5]

Fig. 8 shows an example of optical inspection of a printed pattern. A Hamamatsu C10000 TDI-CCD camera was used for this experiment. Test conditions: optical magnification 30x, object speed 100 mm/s, line rate 40 kHz.

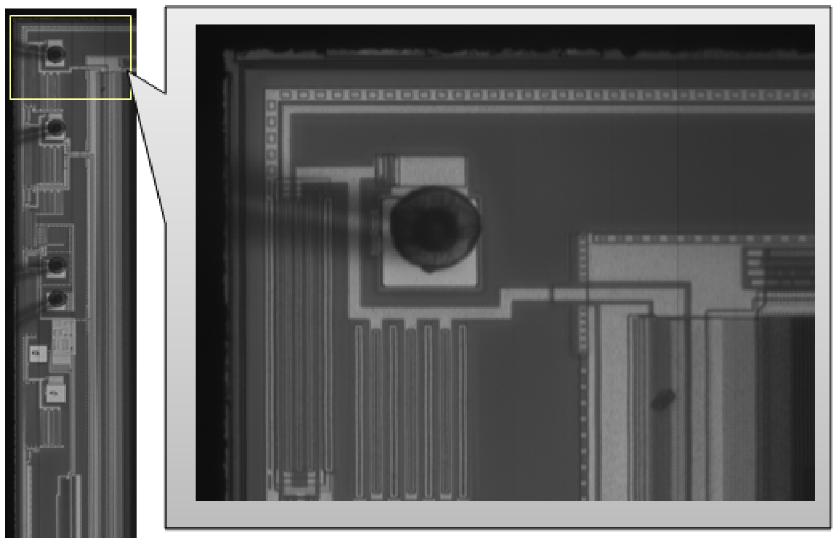

Figure 8: Optical inspection of a printed pattern

An x-ray image of a PCB with SMT components taken with a Hamamatsu C10650 x-ray TDI camera is shown in Fig. 9.

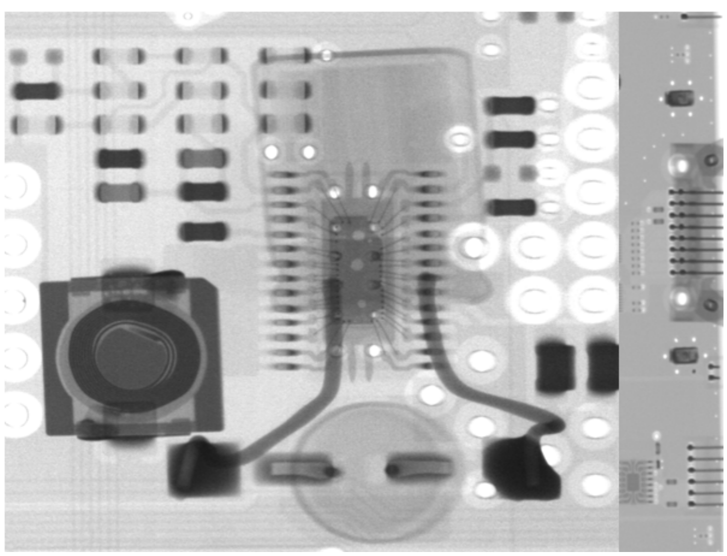

Figure 9: X-ray image of a PCB with SMT components

Recently we have observed a growing interest in TDI linear sensors for 3-D x-ray inspection systems. It has been suggested that implementation of eight linear sensors would be considered a practical minimum for most inspection applications.[6]

While any number of linear sensors may be employed to generate different viewing angles of the object being inspected, a range of twelve to sixteen linear sensors appears to generate a sufficient number of images for proper PCB inspection. In many cases, the use of more than sixteen linear sensors does not add significantly to the inspection capability.

References

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3. J. Gilmore and Y. Bulayev, *CCD advances improve TDI imaging techniques,* Laser Focus World (January 2007).

4. A. Theuwissen, *Time-delay and integration charge-coupled devices,* Presentation at Hamamatsu Technology Seminar, San Diego, CA (June 6, 2008).

5. *Semiconductor inspection relies on imaging*, Vision Systems Design (March 2004).

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Introduction

- As a result of heightened requirements for product quality, integrity and reliability of electronic products, the role of wafer auditing and nondestructive testing of printed circuit boards and electronic assemblies has grown at an unprecedented rate
- It is estimated that the cost of a failure decreases by a factor of ten when the error is identified in the course of production instead of in the field
- Optical and x-ray TDI cameras have become one of the most efficient and reliable tools for nondestructive testing and inspection

Topics To Be Discussed Today

- Concepts of TDI imaging
- AOI applications
- AXI applications

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- Concepts of TDI imaging
- AOI applications
- AXI applications

TDI: Time Delay Integration

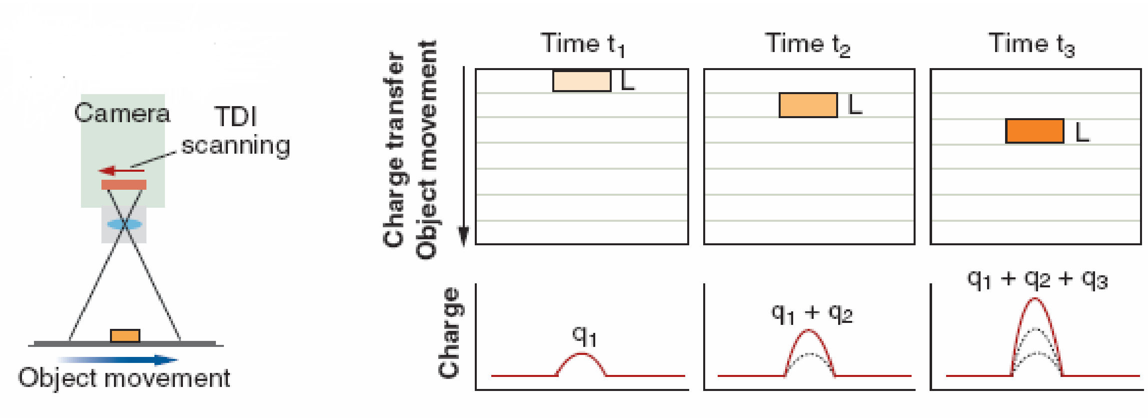
TDI is an effective method for

- Detection of low exposure levels
- Clear imaging of moving objects

By means of

Accumulation of multiple exposures of the same object and noiseless integration of these exposures

Principle of TDI Operation



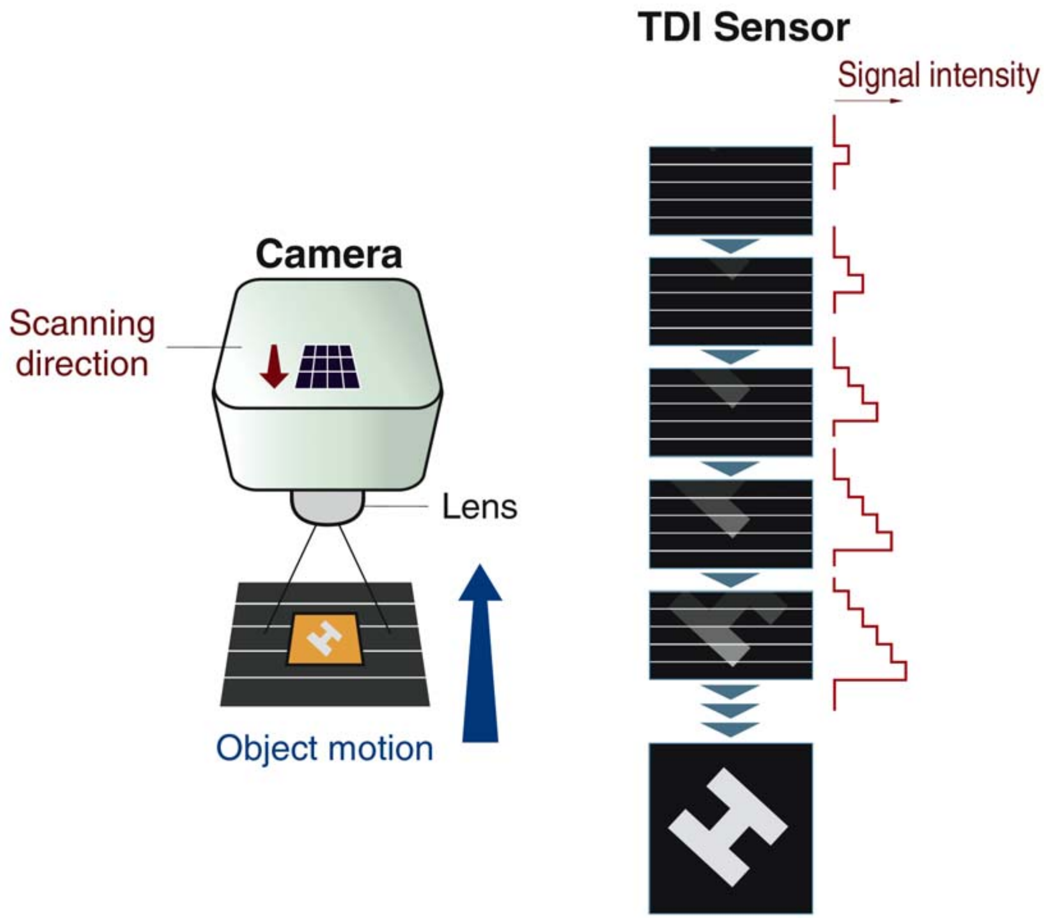
Signal-to-Noise Ratio

Theoretically

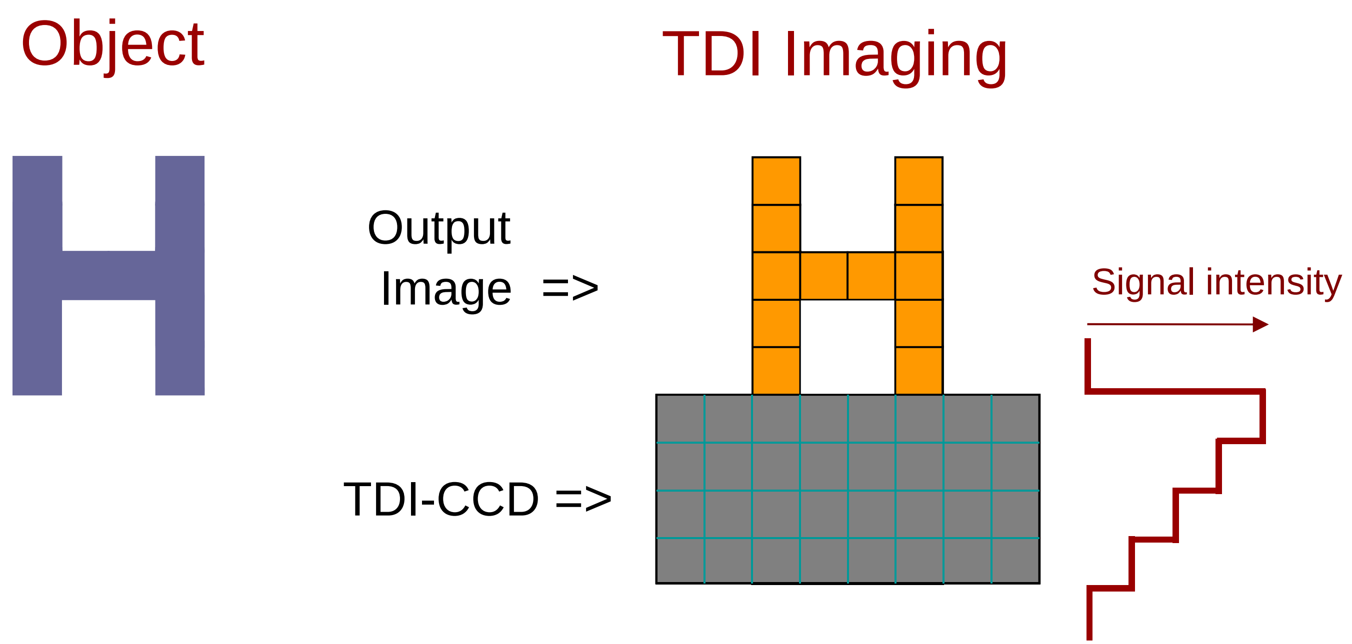
$$SNR_{TDI} = \sqrt{N} \times SNR$$

wherein N - number of TDI stages

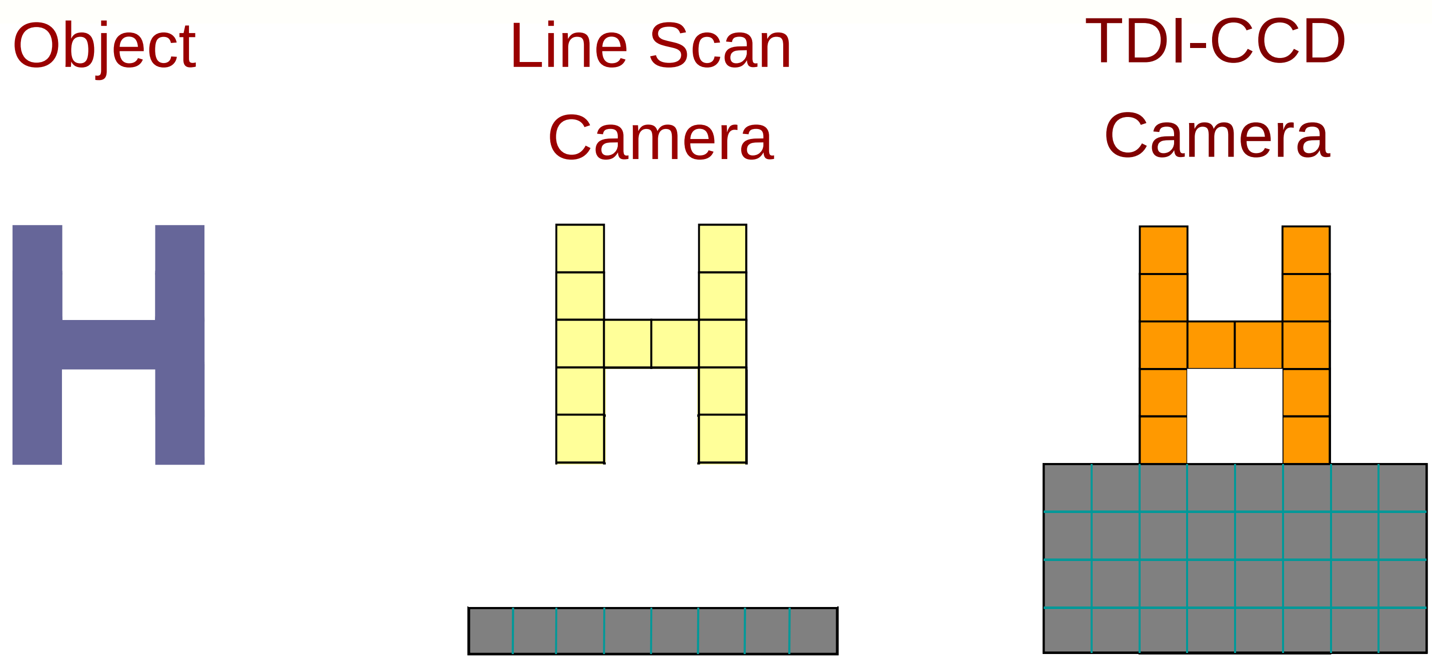
Signal Integration in TDI System



Time Delay Integration



TDI vs. Line Scan Camera

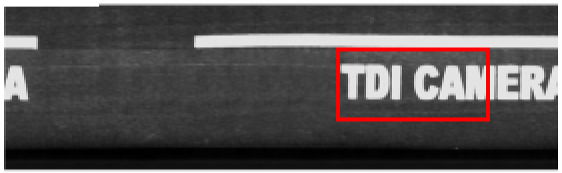


Scan-Velocity Mismatch

TDI Line Rate = Object Velocity
(No Mismatch)

TDI Line Rate > Object Velocity
(10% Mismatch)

TDI Line Rate < Object Velocity
(10% Mismatch)

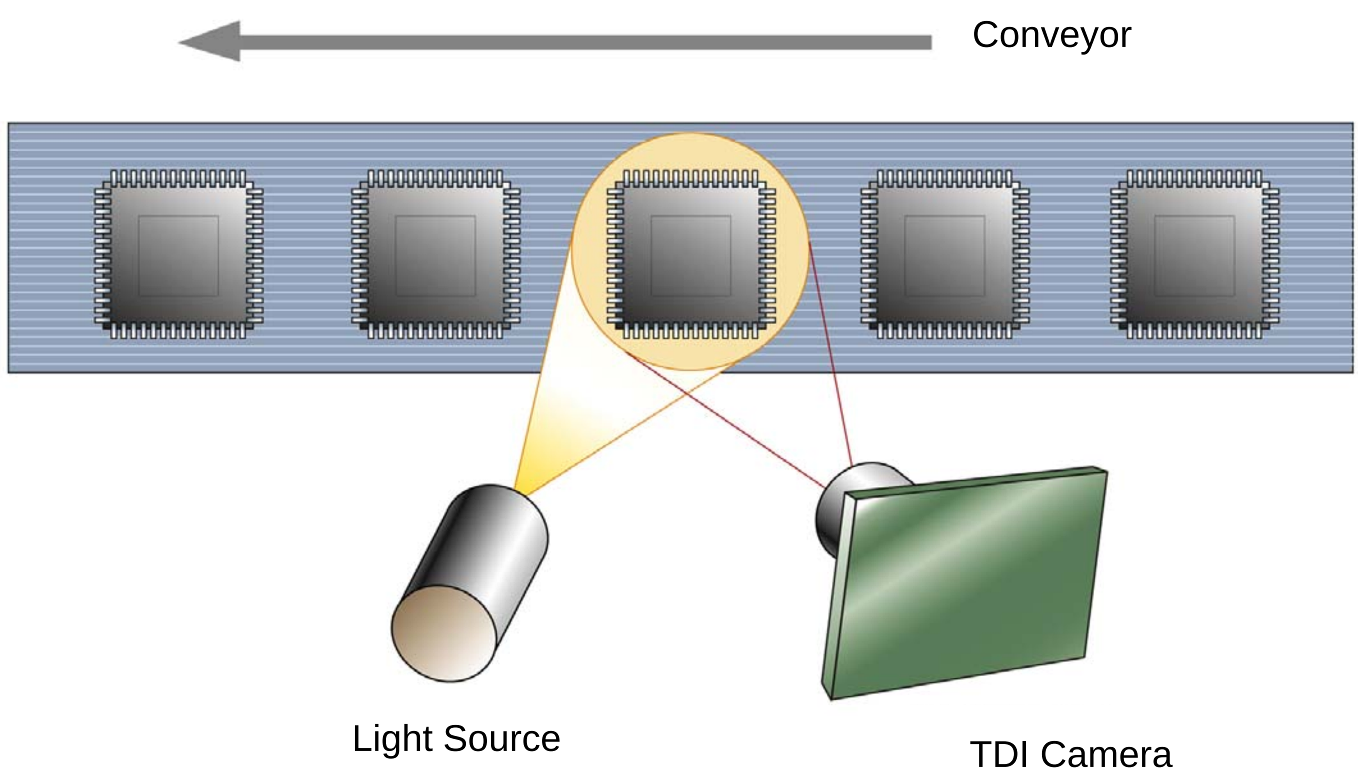


TDI Line Rate << Object Velocity
(~30% Mismatch)

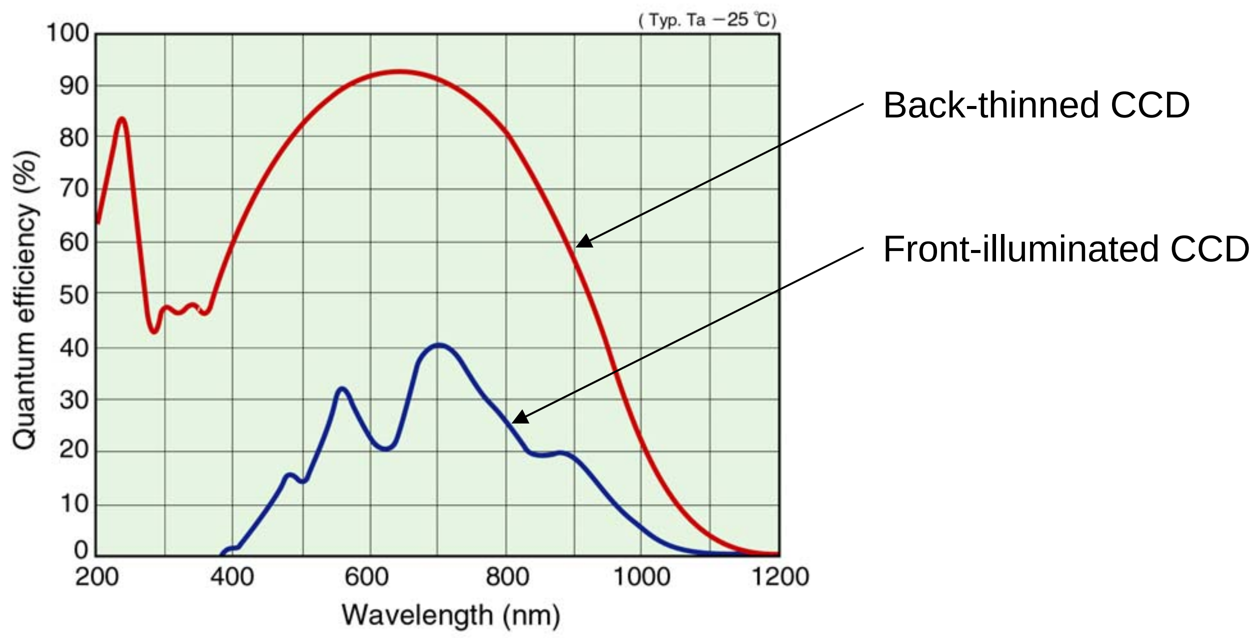
Topics To Be Discussed Today

- Concepts of TDI imaging
- AOI applications
- AXI applications

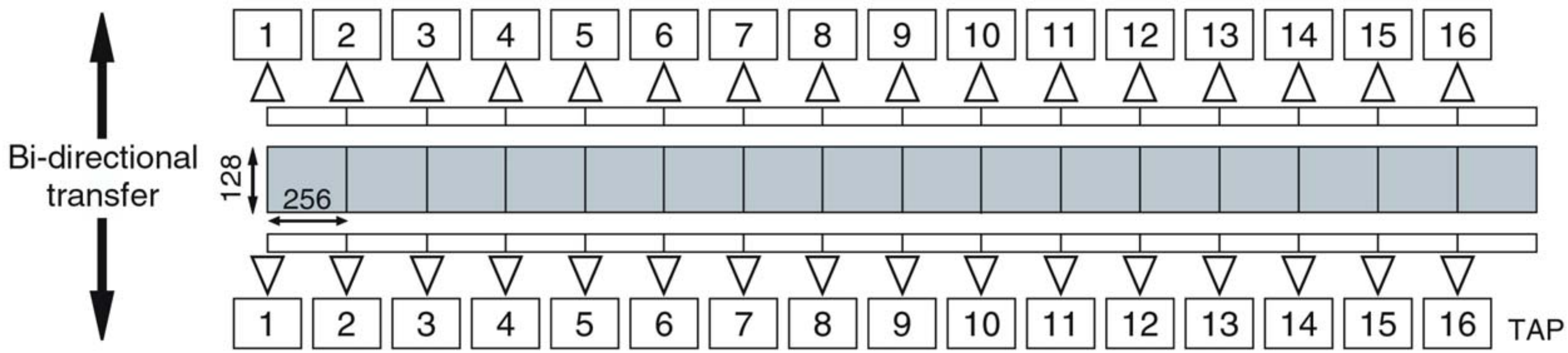
In-Line AOI System



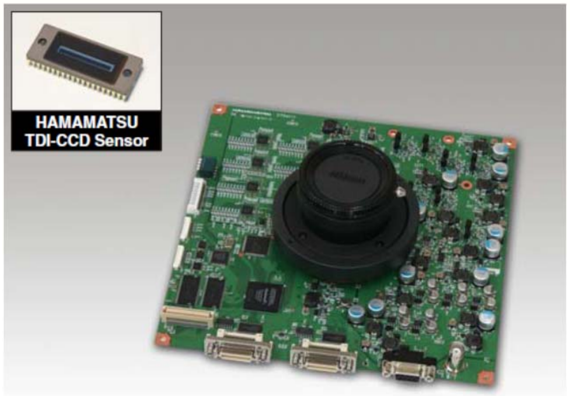
Spectral Response Characteristics



Multitap TDI-CCD Sensor for Bidirectional Scanning



TDI Cameras for AOI Applications

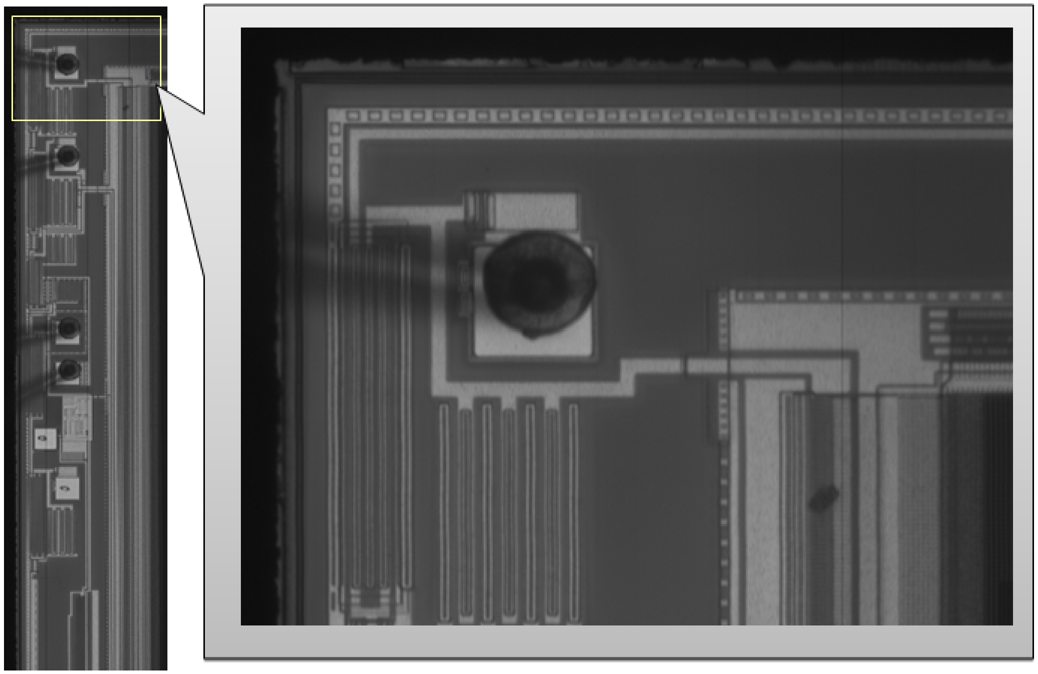


- 2K spatial resolution
- 128 TDI stages
- 12µm x 12 µm pixel size
- Line rate up to 50 kHz

- 2K spatial resolution
- 128 TDI stages
- 12µm x 12 µm pixel size
- Line rate up to 50 kHz

- 4K spatial resolution
-128 TDI stages
-12µm x 12 µm pixel size
- Line rate up to 100 kHz

Optical Inspection



- Optical magnification: 30x
- Object speed: 100mm/s
- Line rate: 40kHz

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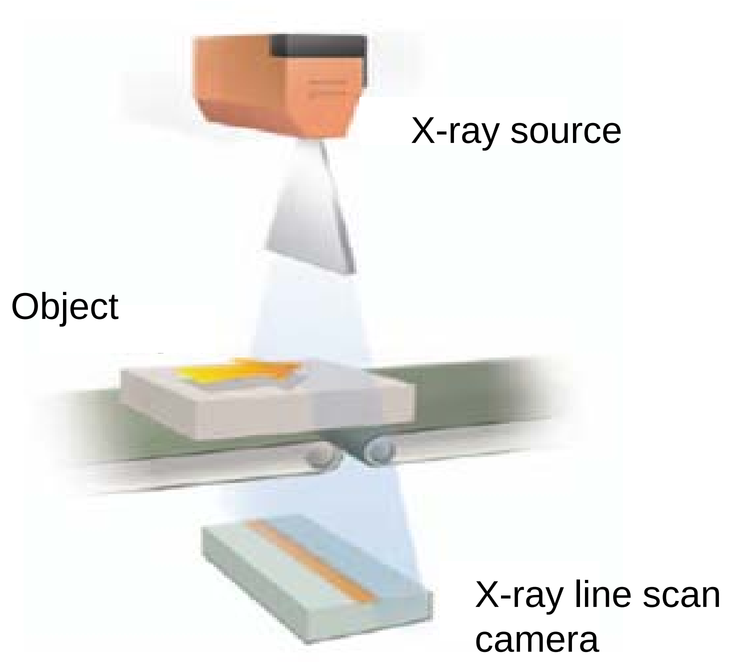
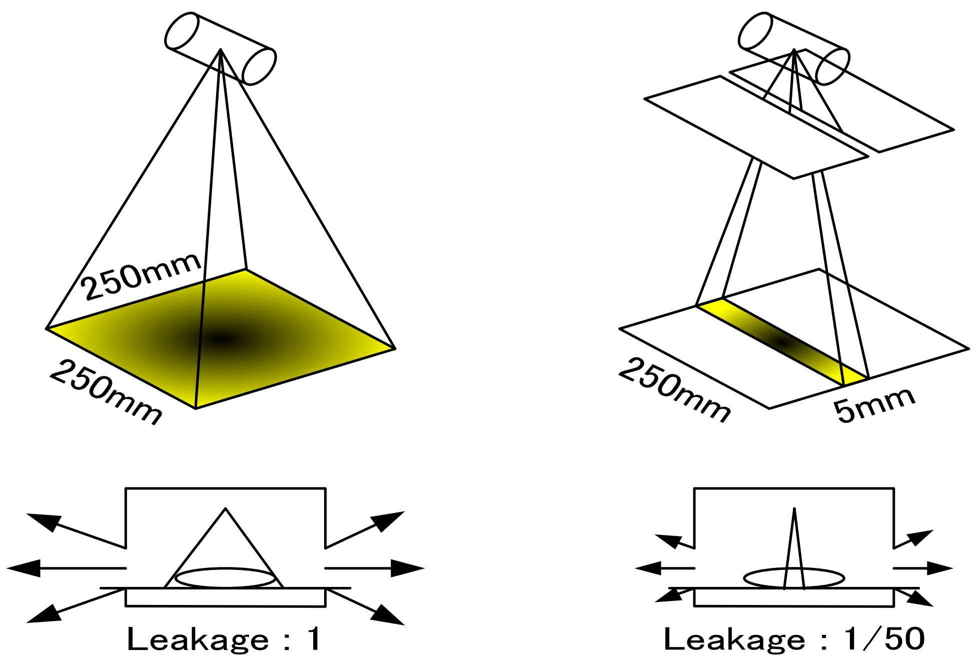
- AXI applications

AXI System



Line Scan Camera vs. 2-D Camera



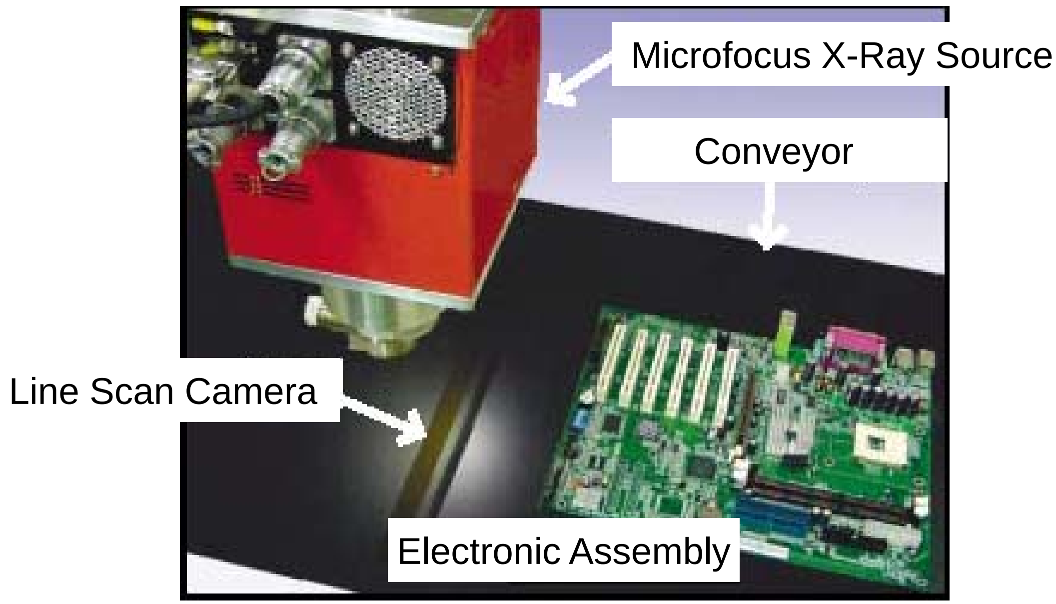
2-D Camera

Line Scan Camera

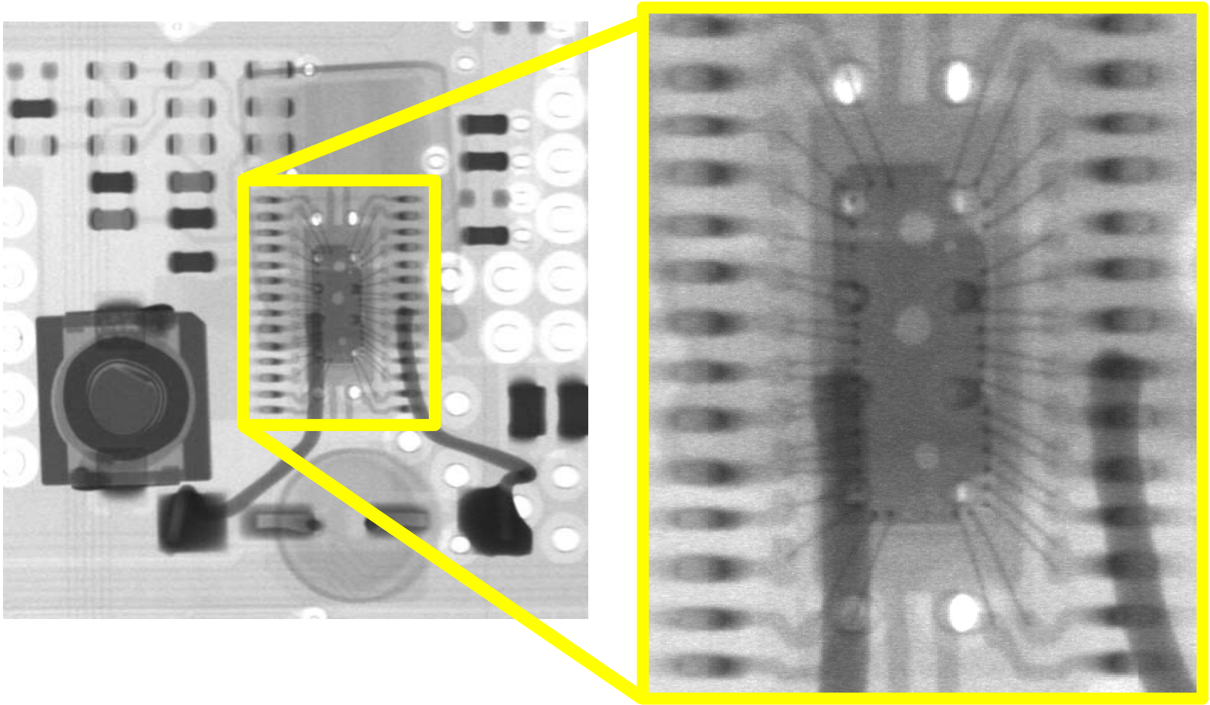
No-gap TDI Camera for AXI Applications

- 292mm detection width
- 6K spatial resolution
- 128 TDI Stages
- 48µm x 48µm pixel size
- 25kVp to 85 kVp X-ray detection range
- Line scan rate up to 2.1kHz

In-line AXI Setup

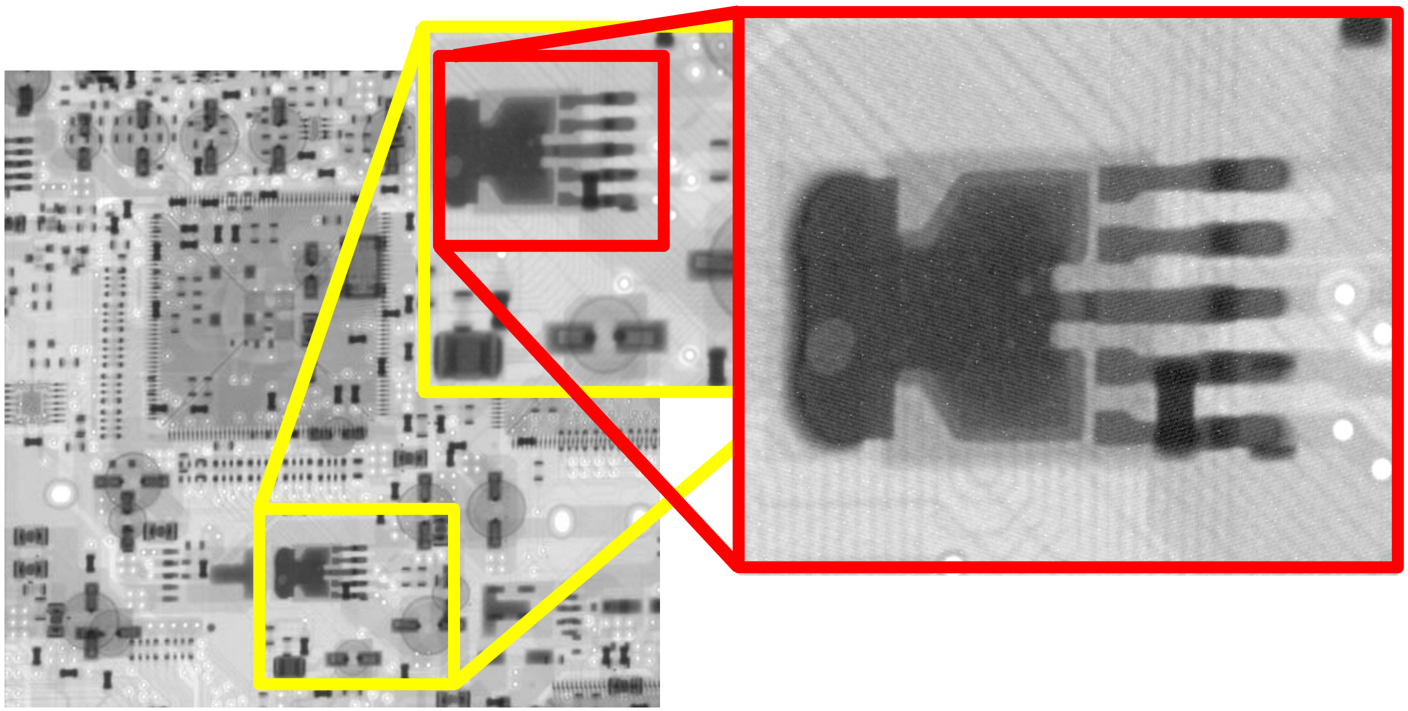


X-ray Inspection (1)



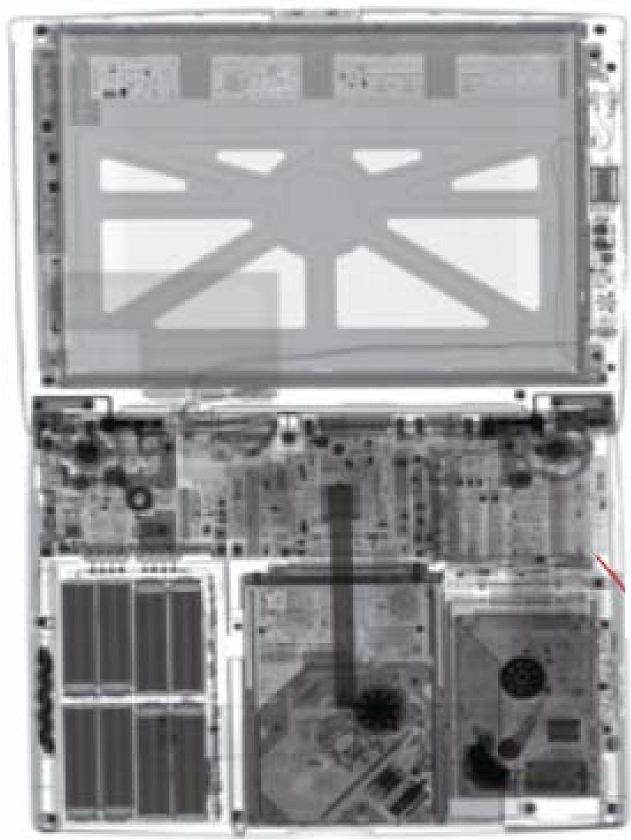
- Geometrical magnification: 1x
- Line scan rate: 1.3kHz
- X-ray source: 110kV, 160µA

X-ray Inspection (2)



- Geometrical magnification: 1x
- Line scan rate: 1.3kHz
- X-ray source: 110kV, 160µA

X-ray Inspection (3)



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