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ORIGINAL ARTICLE

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Design and development of a new machine vision wire bonding inspection system

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Abstract In this paper, we developed a fast and robust machine vision system for wire bonding inspection. The defects caused by a bonding wire being broken, lost, shifted, shorted, or sagged in an integrated circuit (IC) chip can be inspected automatically. A new lighting environment was devised which will highlight the slope of the bonding wire and suppress the background from being extracted. First, a set of machine vision algorithms were designed to filter out the defects of broken wire, lost wire, shifted wire, and shorted-out wire. Second, the 3-D type defect of sagged wire can be detected by inspecting the change of the bonding wire slope, derived from a single 2-D image. Some illustrations are given to show the efficiency and effectiveness of the proposed novel wire bonding vision inspection system.

Keywords Machine vision · Wire bonding inspection · Lighting environment

1 Introduction

Wire bonding is the process that makes the connection between an integrated circuit (IC) chip and the substrate. Bonding the wires onto the IC chip is a very critical procedure. Because the original connecting areas of an IC chip are too small to be welded onto the printed circuit board (PCB), some kind of substrate is devised and used as the connecting medium between the IC chip and the PCB. Each of the connections on an IC chip is called a pad. The interval between two adjacent pads is generally referred to as the pitch. The internal connector on the substrate is called a lead. Typically, a high purity (99.999%) gold wire is used to connect the pad and its corresponding lead. A bonding ball is formed on the pad and a bonding stitch is formed on the lead. The image of a whole chip with about 100 surrounding wires is shown in Fig. 1. Part of the enlarged wire-bonded IC image is illustrated in Fig. 2.

This paper presents a vision inspection system for automatically detecting the possible defects of the bonding ball and the bonding wire. At present, some commercial automatic inspection systems have been used to examine the quality of the circuits on the substrate [1]. However, most wire bonding inspection operations are still executed by human inspectors. The slow speed of human inspectors cannot match the high production rate (about 5 wires per second) of the IC chip production line. As a result, the inspection of the wire bonding is forced off of the line and on a sample basis only. Fatigue and the inconsistency in the vision ability of human inspectors make the traditional inspection operation unreliable. In this paper, a fast and robust machine vision system is proposed for the automatic inspection of the wire bonding process.

There are three focal points in the proposed inspection system: (a) the position of the bonding ball; (b) the position of the bonding wire; and (c) the height of the bonding wire. Because the circuits, leads, and chips on the substrate will reflect more light into the camera than the bonding balls and the bonding wires, the image of an IC chip extracted in this manner will be very complex. To speed up the inspection process, we set up a new lighting environment to simplify the extracted image of the IC chip by preventing the background from being captured. At the same time, the new lighting environment highlights both the bonding wires and the slope change of each bonding wire.

The first focus of the proposed vision inspection system is the position of each of the bonding balls. The bonding ball should normally be placed in the center of the pad. But either the human operator or the bonding machine may cause some error in positioning the bonding ball. In addition, the size of the IC chip, pad, and pitch is getting smaller and smaller, making it more difficult for the human inspector to inspect the position of the bonding ball. Even a slight shift of the ball position may cause an electric short

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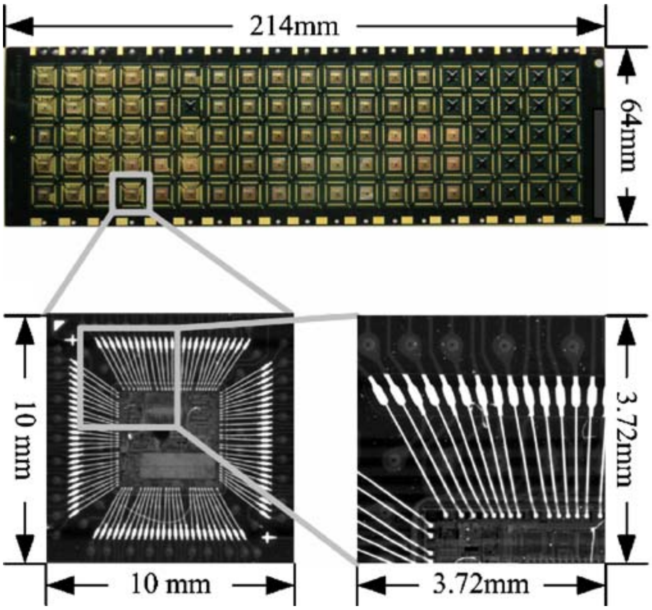


Fig. 1 Diagram of integrated circuit (IC) chips with bonding wires on the substrate

between two adjacent pads. We developed a "modified pattern matching method" to detect and inspect the position of the bonding ball accurately and quickly.

The second focus of the proposed vision inspection system is the position of each of the bonding wires. The bonding wire is about 0.001 inch in diameter. Static electricity or outer force may cause the wire to be broken, lost, shifted, or shorted-out. To filter out any possible error in the wire bonding process, a set of associated inspection algorithms were also proposed.

The third focus of the proposed vision inspection system is the height of each of the bonding wires. A bonding wire that has its height collapsed is called a sagged wire, which

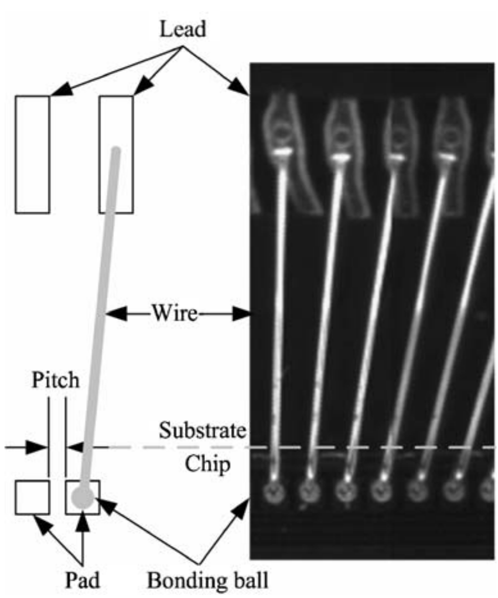


Fig. 2 Illustrative and enlarged image of a wire-bonded IC chip

is very hard to detect from a single 2-D image. Therefore, a good lighting environment which can show the gray-level change of the bonding wire highlighted in great detail is required. This paper presents the lighting mechanism and the modified methods presented in [2] for the sagged-wire detection.

There are usually many IC chips with the same layout of associated leads arranged as a 2-D array on a substrate as shown in Fig. 1. All of this information can be found in the corresponding electronic CAD data file. The proposed inspection system repeats the inspection algorithm for each IC chip on the substrate. All of the bonding wires which surround the IC chip will be captured as four inspection images by the proposed inspection system. One inspection image covers the whole set of bonding wires along one of the four sides of the IC chip. All of the bonding wires on the IC chip thereafter can be inspected by using algorithm 1.

Algorithm 1: Bonding wire inspection of the IC chip

Input: an electronic CAD data file of the bonding wire
Output: the detected defects of the bonding wire
Procedure

Load the electronic CAD data file from the bonding machine
For i=1 to R **do** /*R is the number of rows of the IC chip on the substrate*/

For j=1 to C **do** /*C is the number of columns of the IC chip on the substrate*/

Move the camera to the initial position of the IC chip (i, j) and search for the calibration point on the substrate
For k=1 to 4 **do**

Capture image(k) of the bonding wires of one side of the IC chip /*image(1), image (2), image(3), and image(4) correspond to the bonding wires in the up, right, down, and left side of the IC chip*/
Procedure **Bonding ball inspection** /*Compare the position of the bonding balls in the images with the electronic CAD data*/
Calculate the position of each of the leads in image(k) by using the coordinates in the electronic CAD data file and the pixel size rate
Procedure **2D bonding wire inspection** /*Detect possible 2-D type defects of the bonding wires*/
Procedure **3D bonding wire inspection** /*Detect possible sagged bonding wire*/

End for

End for

End for

End procedure

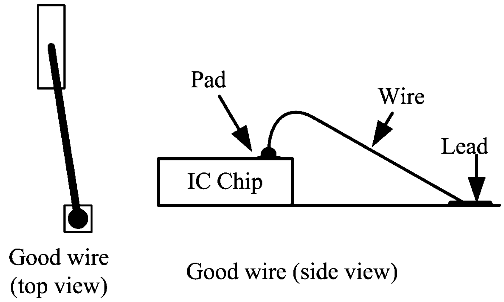


Fig. 3 Illustration of good bonding wire

This paper is organized as follows. In Section 2, we present some related researches of wire bonding inspection. The experimental equipment, proposed lighting environment, inspection algorithms, and illustrative examples are described in Section 3. Our conclusions are given in Section 4.

2 Related researches

Ahmed et al. [3] discussed a 2-D inspection system that can check: (a) the bonding capillary marks, which should not exceed the pad boundary; (b) the scratches on the pad, which must not exceed 50% of the pad width; and (c) the bonding capillary marks, which must not exceed 25% of the pad area. The algorithm extracted the capillary marks by using a local threshold method. It also identified the protrusions of the marks beyond the pad boundary by using a morphological filter.

Khotanzad et al. [4, 5] presented an automatic system for inspecting the quality of the bonding ball which connects the pad and the bonding wire. This system could determine the location of the bonding ball from an ordinary image, which was taken from the top view of an IC wafer, and could extract geometric measures about the contour of the bonding ball. These measures were obtained by using the best-fitting ellipse for the bonding ball. They used the Sobel operator [6] to enhance the original images, and Otsu's [7] threshold technique to binarize the enhanced images. The approximate center of the bonding ball was first determined by using a morphological erosion operation. Then, the bonding ball contour was found by scanning this center radially. Finally, the parameters of the best-fitting ellipse could be computed by using analytic geometry techniques [8].

Ngan and Kang [9] presented an algorithm for the bonding wire inspection. There were two main procedures: (a) generating candidate points of the bonding wire and (b) determining the equation of the bonding wire. They used a 1-D gradient threshold technique to generate the "candidate point" of each bonding wire. They treated the candidate point as the starting point of the bonding wire. The Hough transformation [10] is used to find out the straight-line equation of the bonding wire. Only (a) missing or extra wires and (b) crossing wires were detected by this algorithm.

Some studies presented different vision systems which can inspect the position of the bonding wire and/or the contour and position of the bonding ball. However, none of these vision systems can detect the error in the wire height. Ye et al. [11] presented a stereo vision system for wire height inspection. In a single-camera-based setup, stereo views are obtained by rotating the IC chip. They captured the first image of the chip and rotated the chip by 180°, and then captured the second image. The edges of the wires are detected by using Petrou's line filter [12]. The facet model proposed by Haralick and Shapiro [13] is applied to obtain sub-pixel edge localization. Based on the positions of the wires in a pair of images, the height profile of each of the bonding wires was obtained by using a disparity equation derived from the image geometry.

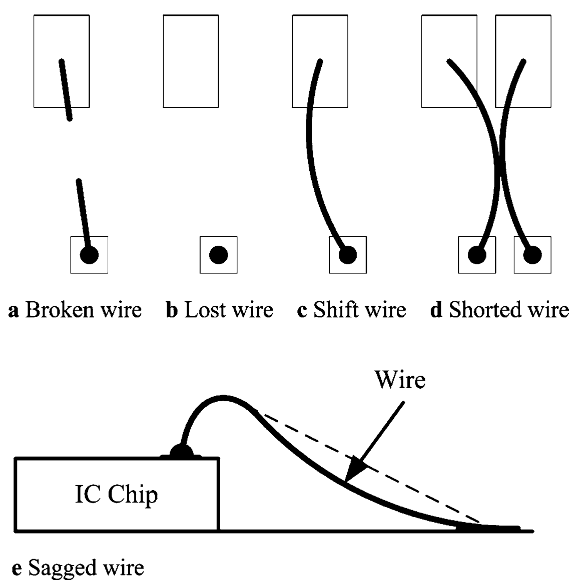


Fig. 4 Illustration of the five possible bonding wire defects

3 Inspection algorithms for bonding wire

In contrast to good wire, as illustrated in Fig. 3, there are five kinds of defects that will appear in the wire bonding process: broken wire, lost wire, shifted wire, shorted wire, and sagged wire, as illustrated in Fig. 4. As indicated in the

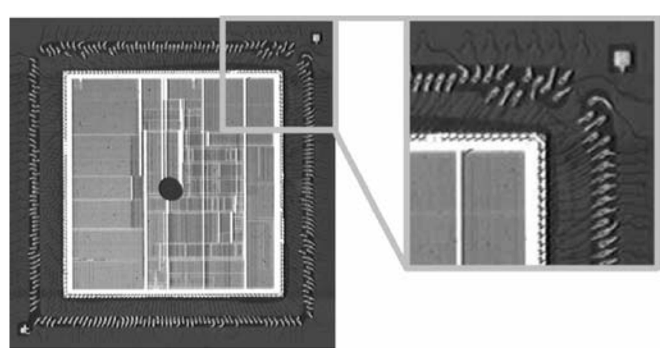


Fig. 5 Image of an IC chip under ordinary vertical lighting

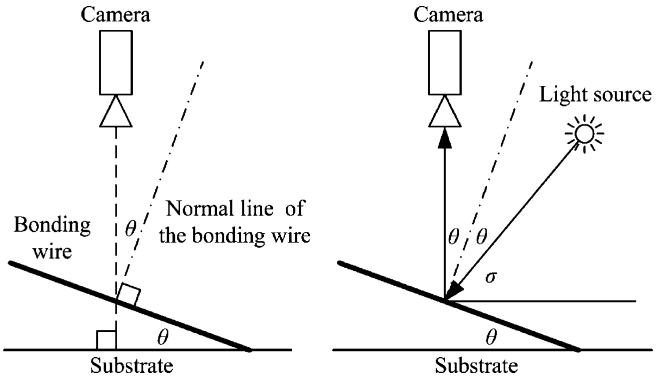


Fig. 6 Illustration of the bonding wire reflection model

literature, the former four defects can be detected by using an ordinary 2-D vision inspection system, while the sagged wire defect can only be detected by using a stereo vision technique.

Some researchers used pre-processing algorithms to remove the complex substrate background from the image. Additional pre-processing time is spent in removing the substrate background. In this paper, we designed a new lighting environment which can inherently enhance the bonding wires and can, simultaneously, suppress the substrate background. Consequently, the background image removing operation is eliminated and the processing time is reduced. We can focus on the inspection of the bonding ball and the bonding wire. Because the bonding wire connects the pad and the lead, the circular contour of the bonding ball is broken by the connected wire. This makes the center of the bonding ball hard to be detected. Instead of using the time-consuming best-fitting ellipse method to find the circular contour of the bonding ball, we developed (a) a modified pattern matching method to determine the center of the bonding ball and (b) a set of algorithms to filter out all possible defects of the bonding wire. With the aid of the newly designed lighting environment, we can capture a better quality image of the IC chip, so that the gray level of the pixels in the image can be used for checking the slope of the bonding wire. Also, the 3-D type defect of sagged wire can be detected by the proposed 2-D vision inspection system instead of a stereo vision system.

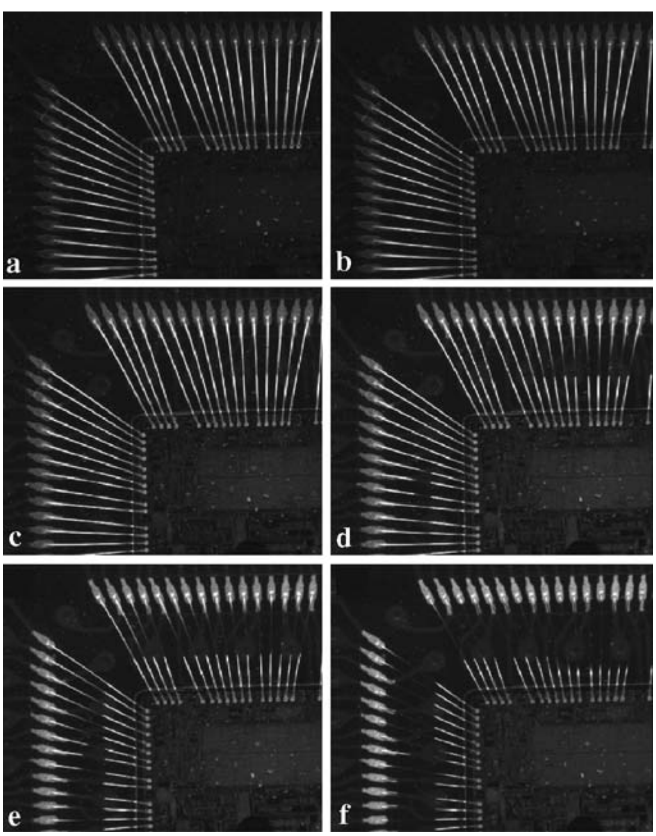


Fig. 7 Images of the bonding wire under different lighting angles. The bonding wires in image **b** have a better lighting effect

3.1 Lighting environment

Usually, a vertical light source is used for capturing the image of an IC chip. The circuits and leads and the background material of the IC chip on the substrate are a kind of reflecting object. More light will be reflected into the camera by these objects than by the bonding wire. This will increase the complexity of the image of the bonding wires; this means that the focus of the captured image be lost. In Fig. 5, the bonding wires were very vague or had disappeared in the image under ordinary vertical lighting.

To have the bonding wires appear clearer in the image, we must have the bonding wires reflecting more light into the camera. We assume that a bonding wire is at $\theta°$ to the horizontal plane. Following the general reflection rule, the incident angle of the light should be set at $\theta°$ to the normal line of the bonding wire or at $\sigma°$ to the horizontal plane, and then the light will be reflected into the camera directly from above, as shown in Fig. 6. The relationship between the incident angle σ and the given bonding wire slope θ is:

$$\sigma = 90° - 2\theta \quad (1)$$

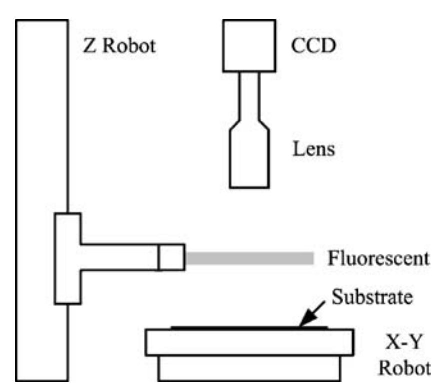


Fig. 8 Experimental equipment for wire bonding inspection

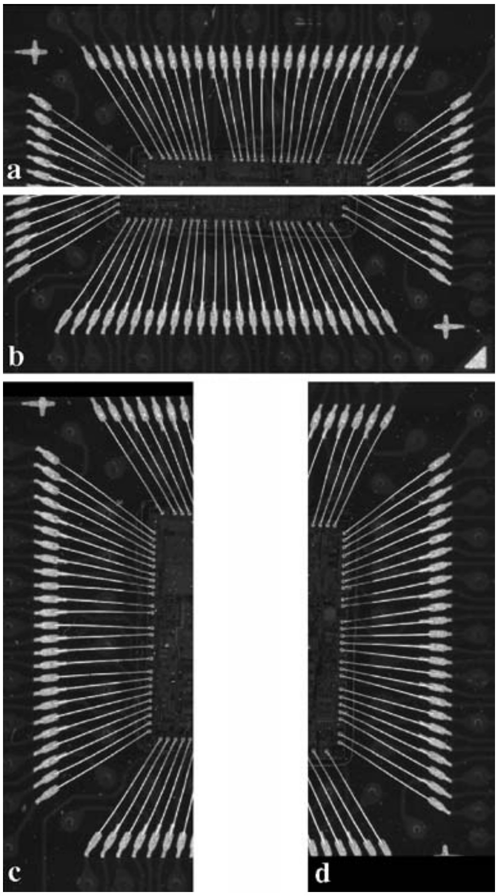


Fig. 9a–d Inspection images of the experimental IC chip. **a** Up side. **b** Down side. **c** Left side. **d** Right side

We used a ring type fluorescent light as the light source and installed it at a proper angle following Eq. 1. Then, the light reflected from the circuits, leads, and background material to the camera will be less than that from the bonding wires. That is, the wires will appear clearer than the other objects in the captured image with properly set up light source. Figure 7 shows some captured images of an IC chip and its associated wires under different angles. If the light source is set up at a lower angle, then the circuits, leads, and background material are darker in the image. The bonding wires are at 35° to the horizontal plane, so when the light source is set up at an angle near to 20° (by Eq. 1), the bonding wires will be clearer than the other objects. Therefore, the wire inspection can be carried out without any pre-processing to remove the background from the captured image.

Besides eliminating the background from the captured image, the properly set up light source can also assist in detecting the 3-D defect of sagged wire. This will be described in Section 3.5.

3.2 Experimental setup

The equipmental setup for these experiments of the bonding ball and the bonding wire inspection is shown in Fig. 8. A *Z* robot moves the ring type fluorescent light to set the proper height and an *X–Y* robot moves the substrate for image capturing. All of the images of the bonding ball and the bonding wire were taken using a JAI CV-A1 B/W camera of 1,392×1,050 resolution. The optical rate of the lens was 1×. The physical size of the IC chip was about 6×7 mm. The physical width of one pixel was 4.65 um. The size of the inspection window was 7.6×6.2 mm. The inspection algorithms were programmed using Microsoft Visual Basic 6.0 and Matrox MIL 6.0. The experimental computer was powered by an AMD Athlon 1GHz CPU.

We used an IC chip with 100 bonding wires, as shown in Fig. 1, as the experimental example. Each inspection image covered 25 bonding wires along one side of the IC chip. The inspection time of each inspection image was 0.5 s, including the bonding ball, 2-D bonding wire, and 3-D bonding wire inspections. It took about 0.02 s to inspect one bonding wire, on average. All of the defects of the bonding wire could be detected by the proposed algorithms. Figure 9 illustrates the four inspection images of the IC chip.

3.3 Bonding ball inspection

3.3.1 Algorithm of bonding ball inspection

Former researchers focused on inspecting both the contour and the position of the bonding ball. Today, bonding machines are good enough that the contour of the bonding ball is accepted as it is. Inspectors need only focus on the position accuracy of the bonding ball. The best-fitting ellipse method [4] usually requires a long calculating time to search and refine the contour of the bonding ball, which makes it difficult to synchronize the inspection process with the production line. Therefore, a simple method is required to determine the position of the bonding ball.

Pattern matching is a popular method to search for objects of similar property in an image. The wire

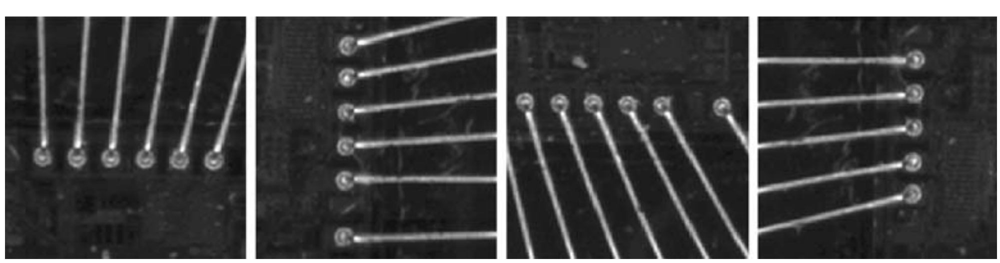


Fig. 10 Images of the bonding ball with varying shapes of contour

Fig. 11 Search model of an exemplified bonding ball (19×14 pixels, 4.65 um/pixel)

connecting the center of the bonding ball with the lead on the substrate is found in four directions of the image: up, down, left, and right. Each connecting position of the wire with the bonding ball may not be the same, and, therefore, an original pattern matching method cannot be applied directly to search for the bonding ball. In Fig. 10, we show four images of the bonding ball. Each image, as a part of one side image of the IC chip, has wires connecting with the balls in different directions. We can also see that the bonding balls in the image have similar but varying contour shapes compared to that of other images.

However, if the lead of a pad was found in the upper portion of the image, the wire will affect only a small upper part of the contour of the bonding ball. The remaining part (the lower portion) of the contour is still of the same shape. So, we can take the remaining lower portion, which is about 60% of a full bonding ball, as a search model for our pattern matching approach. Similarly, if the bonding wire goes to the lower side, we take the upper 60% part of the full bonding ball as the search model, and similarly for the left and right side cases. This modified pattern matching method can quickly and accurately search for and detect the positions of all of the bonding balls in each of the four side images of IC chip.

If the position shift of the bonding ball is larger than the specification, then the connected bonding wire will be marked as a shifted wire, and will be ignored in the next inspection procedure. The method used to check the position of bonding ball is described in algorithm 2.

Algorithm 2: Bonding ball position inspection

Input: four images of the bonding wires, an electronic CAD data file of the bonding wires
Output: the position of the bonding ball, the index of the shifted wire

Procedure bonding ball inspection

For i=1 to 4 **do**

Calculate the approximate position of the upper-left bonding ball, which is closest to the original point of image(i), according to the electronic CAD data file of the bonding wire
Find the first bonding ball in image(i) by the modified pattern matching method
Find out all of the other bonding balls in image(i) by the modified pattern matching method /*The first bonding ball is used as a reference for later processing*/
For j=1 to B **do** /*B is the total number of bonding balls in image(i)*/

If the position of bonding ball(j) is larger than the specification

Mark bonding wire(j) which is connecting bonding ball(j) as a shifted wire

End if

End for

End for

End procedure

3.3.2 Illustration of bonding ball inspection

An exemplified search model, consisting of 19×14 pixels, for describing the bonding ball inspection process is shown in Fig. 11. According to the position of the calibrating point on the substrate, and the file of the bonding data, we can calculate the approximate region of each of the bonding balls in the image. This search model was used to search for every bonding ball in these regions. Figure 12 illustrates the detected results of the bonding balls of the images as shown in Fig. 10. Each cross-hair in the image represents the determined center of each bonding ball. The correlation coefficient [9] derived by the pattern matching method represents the difference between the search model and the image of the detected result. All of the correlation coefficients of the bonding ball obtained by the proposed approach are higher than 70%. This level of correlation coefficient is qualified for detecting the bonding ball in real practice.

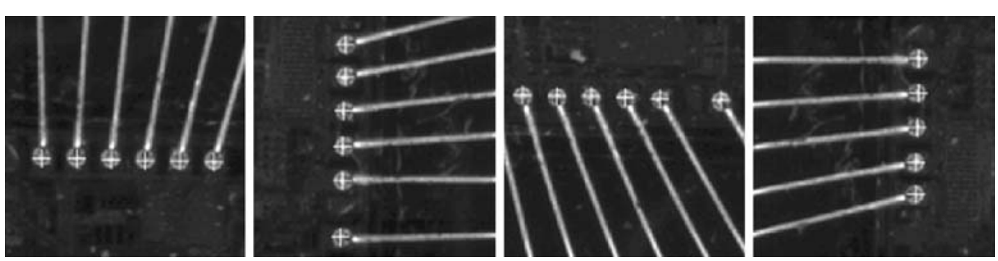


Fig. 12 The detected results of the bonding balls of the images as shown in Fig. 10. The ball with a cross-hair mark means it was found by the proposed pattern matching method

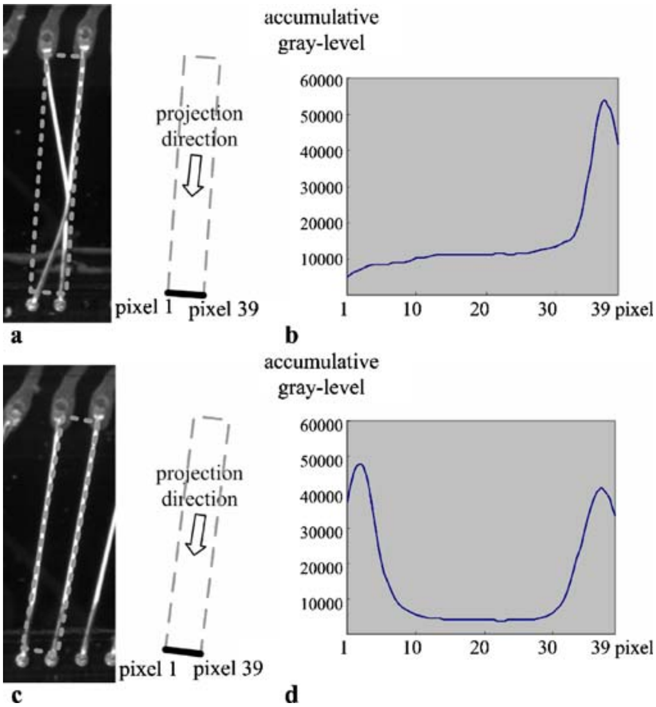


Fig. 13a–d Inspection for shorted wires. **a** Shorted wires and the illustrative projection method. **b** Projected profile of the shorted wires. **c** Good wires and the illustrative projection method. **d** Projected profile of the good wires

3.4 2-D inspection of bonding wire

In inspecting the bonding wire, the shorted wire in the image will be detected first, followed by the case of shifted, broken, or lost wire. The case of sagged wire will be detected lastly.

3.4.1 Shorted wire inspection

3.4.1.1 Algorithm for shorted bonding wire inspection In the wire bonding process, the bonding machine will first find a pair of pre-designed special marks on the IC chip and the substrate of each IC chip. These marks are designed as the calibrating points to locate the substrate and the IC chip. The corresponding electronic CAD data has to be read in from a stored file prior to starting the wire bonding process. The electronic CAD file records the position of the calibrating points and the relative position of each of the pads, leads, and bonding wires. After the calibrating process, the bonding machine will then start the process of connecting each pad to its corresponding lead by a golden wire.

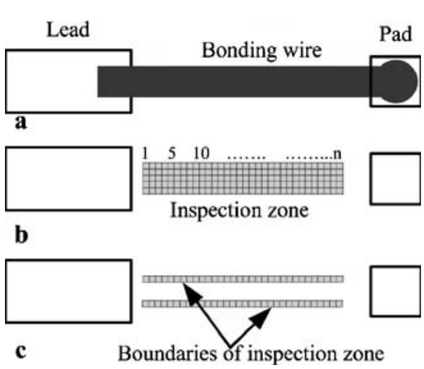


Fig. 14a–c Illustration of the inspection zone of a bonding wire. **a** Illustration of a bonding wire. **b** Illustration of the inspection zone, where each grid represents a pixel. This inspection zone is of 5 pixels wide and *n* pixels long. **c** Illustration of the boundaries of the inspection zone

To inspect a bonding wire, we need to extract the positions of all pairs of start points (bonding ball) and end points (lead). First, we find the position of each of the bonding balls as described in Section 3.3. Then, we calculate the position of each of the leads on the substrate. The position of the lead is calculated as follows. We take a stored image of the calibrating mark as a template and detect the position of a pair of calibrating marks in the image by the pattern matching method. The relative position of every lead can then be calculated with reference to the electronic CAD bonding data file.

As to the errors of the bonding wire itself, the most serious case is the shorted wire. We used the projection method to check a rectangular region in which every two adjacent wires are covered. The number of pixels and associated gray levels in this region are summed together in the direction parallel with the bonding wire. If there exists a shorted wire, the profile of projection will not be U-shaped. To speed up the shape checking operation, only the middle one-third of the profile has to be checked. If the number of accumulative gray levels is larger than the pre-defined threshold value, the two adjacent bonding wires will be marked as shorted wires. The following algorithm presents the procedure for shorted bonding wire inspection.

Algorithm 3: Shorted bonding wire inspection

Input: four images of the bonding wires, an electronic CAD data file of the bonding wires
Output: the index of the shorted wire
Procedure

For i=1 to 4 **do**

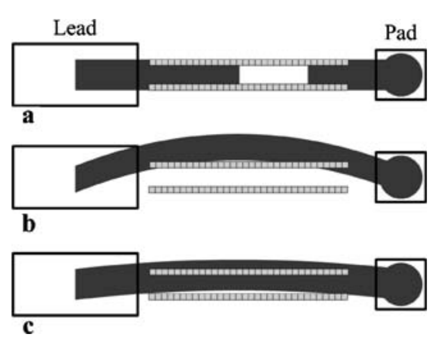


Fig. 15a–c Illustration of the inspection zone of a bonding wire with defects. **a** Illustration of a broken wire. **b** Illustration of a shifted wire. **c** Illustration of a wire that has shifted slightly, but is still located within tolerance

For *j*=1 to *W* **do** /**W* is the total number of bonding wires in image(*i*)*/

Calculate the position of the lead of bonding wire(*j*), according to the electronic CAD data file of the bonding wires

End for

For *j*=1 to *W*−1 **do**

Get the profile of the projection within the rectangular region between and parallel with wire(*j*) and wire(*j*+1)

If the profile of the projection is NOT U-shaped **then**

Mark wire(*j*) and wire(*j*+1) as a shorted wire

End if

End for

End for

End procedure

3.4.1.2 Illustration of shorted bonding wire inspection Figure 13a,b, respectively, shows an image of a shorted wire and the profile of projection method. The dotted rectangle in Fig. 13a, which encapsulates the two adjacent bonding wires, was the region defined for the projection method. When the electrical short occurred for two wires, the profile of projection will expose as a non-U-shape graph, as shown in Fig. 13b. On the other hand, Fig. 13c,d, respectively, shows an image of good wires and the U-shape profile derived by the projection method. It means that there is nothing in between the two adjacent good wires.

3.4.2 Shifted, broken, or lost wire inspection

3.4.2.1 Algorithm for shifted, broken, or lost bonding wire inspection After the inspection for shorted wires, we continue to detect the possible cases of shifted, broken, or

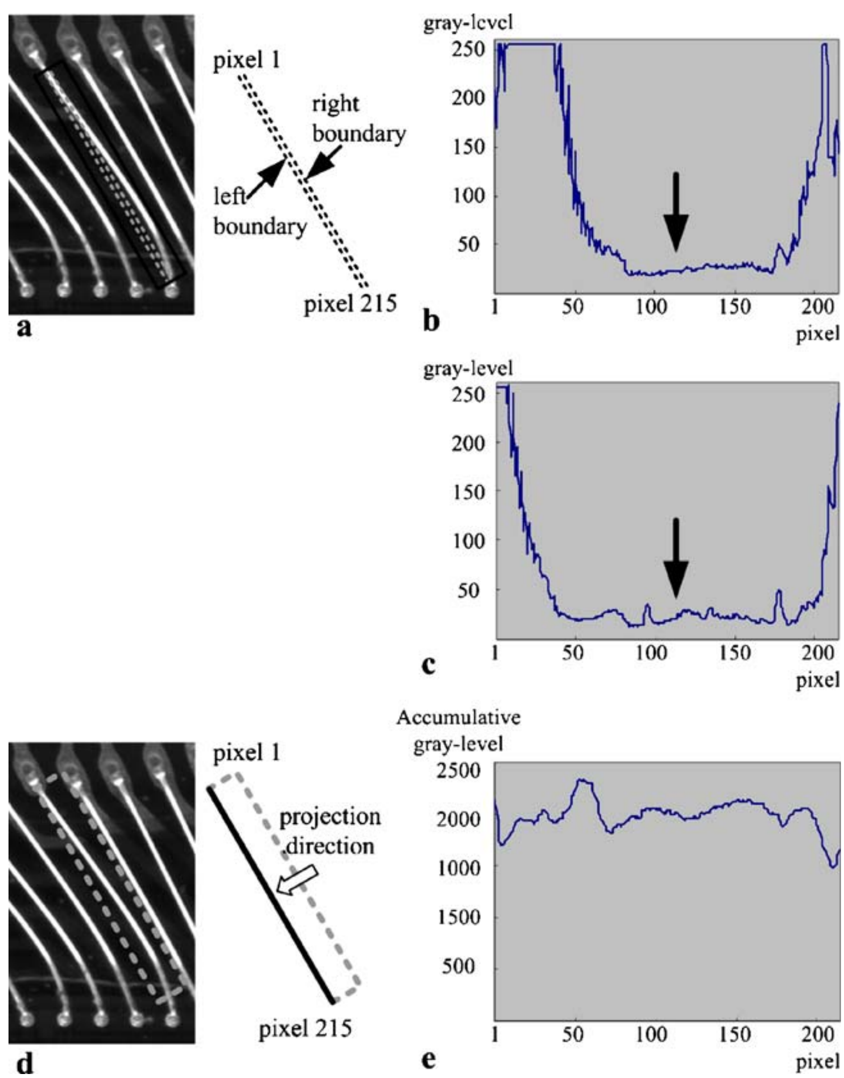
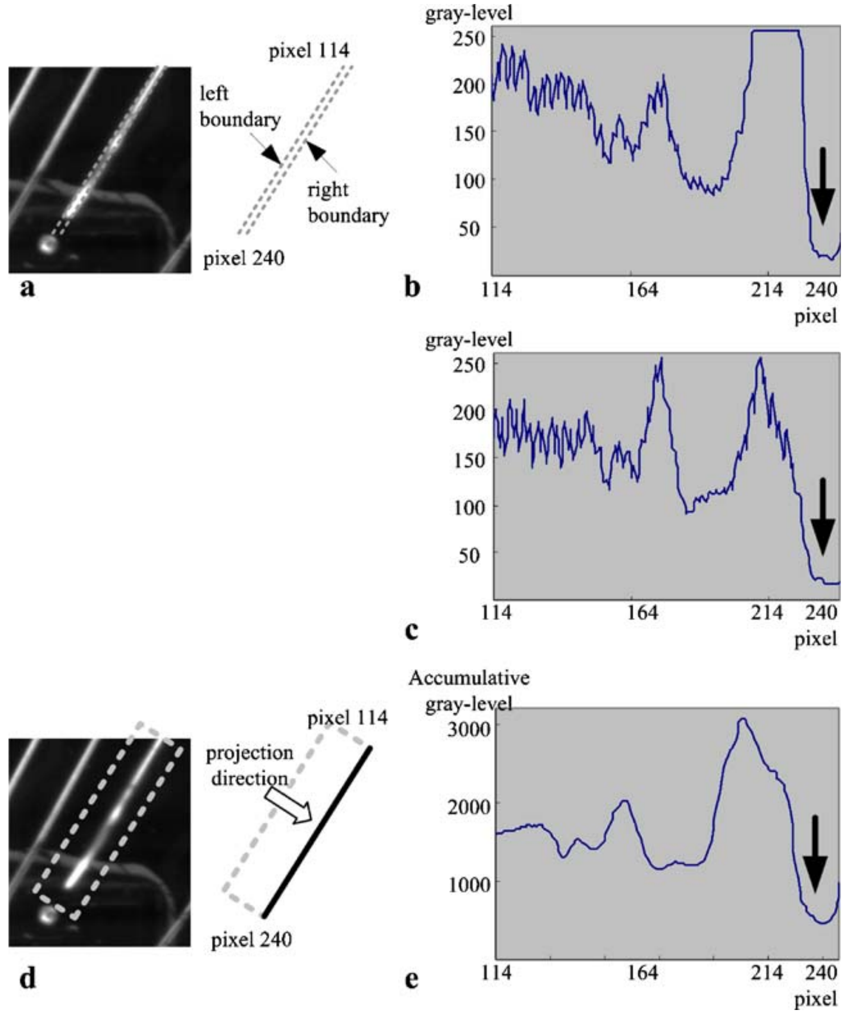


Fig. 16a–e Inspection for a shifted wire. **a** An image of a shifted bonding wire and the illustration of the boundaries of the inspection zone. **b** The gray level of the pixels on the left intersection of the boundary. **c** The gray level of the pixels on the right intersection of the boundary. **d** An image of a shifted bonding wire and the illustration of the projection method. **e** Profile of the projection of Fig. 16d

Fig. 17a–e Broken wire inspection experiment. **a** An image of a broken bonding wire and the illustration of the boundaries of the inspection zone. **b** The gray level of the pixels on the left intersection of the boundary. **c** The gray level of the pixels on the right intersection of the boundary. **d** An image of a broken bonding wire and the illustration of the projection method. **e** Profile of the projection of Fig. 17d



lost wires. A shifted wire is defined as a bonding wire shifted away from its specified location by a distance greater than the allowance. Practically, the allowance is the same as the diameter of the bonding wire. For each pair of bonding ball and its corresponding lead, an inspection zone is established that is of the same width as the bonding wire, between 0.02 mm and 0.05 mm. This inspection zone covers the bonding wire which links the lead to the bonding ball. To shorten the inspection time, only the two boundaries of the inspection zone are checked, as shown in Fig. 14. If a bonding wire is found lying on the boundary of the inspection zone, then the gray level of each of the pixels along the boundary will be higher than a pre-defined threshold. The results of the bonding wire inspection process can be classified into three types:

a. A wire is lost—no wire can be found along the two boundaries of the inspection zone.
b. A wire is broken or shifted—the wire can be found along the two boundaries, but will disappear in a certain segment, as shown in Fig. 15a,b. We use the projection method to distinguish a broken wire from a shifted wire. When a broken wire occurs, an abrupt drop-down will appear in the profile of the projection of the image in the direction perpendicular to the bonding wire.
c. A wire is found to be good—the wire is found within and along the two boundaries of the inspection zone. A wire which has shifted slightly away, but within the tolerance and has disappeared in a certain segment

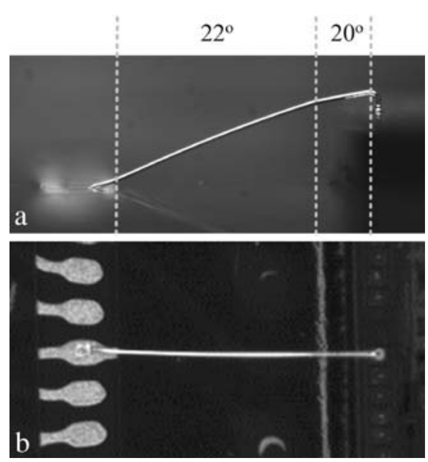


Fig. 18 **a** Side-view image of a good wire. **b** Top-view image of the same wire under the ring type fluorescent light

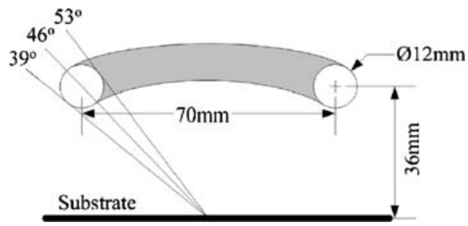


Fig. 19 Illustration of the range of the incident angle of a ring type fluorescent light 70 mm in radius and 36 mm above the substrate

synchronously along one of the boundaries of the inspection zone, may still be recognized as a good wire, as shown in Fig. 15c.

The algorithm of shifted, broken, or lost wire inspection is described in algorithm 4.

Algorithm 4: Shifted, broken, or lost wire inspection

Input: four images of the bonding wires, an electronic CAD data file of the bonding wires
Output: the index of the shifted, broken, or lost wire
Procedure

For *i*=1 to 4 **do**

For *j*=1 to *W* **do** /**W* is the total number of bonding wires in image(*i*)*/

If wire(*j*) is not marked as a defect wire **then**

Calculate the inspection zone(*j*) from pad (*j*) to lead(*j*)
Check the gray level of pixels to verify that the bonding wire lays on either of the two edges of inspection zone(*j*)
Select case the existence of bonding wire on either of the two edges of inspection zone(*j*)
Case the bonding wire is correct on either boundary of the inspection zone(*j*)

Mark wire(*j*) as no 2-D defect

Case the bonding wire disappeared on a certain segment along both boundaries of inspection zone(*j*)

Use the projection method to check wire(*j*), the direction is perpendicular to the bonding wire
If there is a gap in the profile of projection **then**

Mark wire(*j*) as broken wire

Else

Mark wire(*j*) as a shifted wire

End if

Case no wire lies on the boundaries of inspection zone(*j*)

Mark wire(*j*) as a lost wire

End select

End if

End for

End for

End procedure

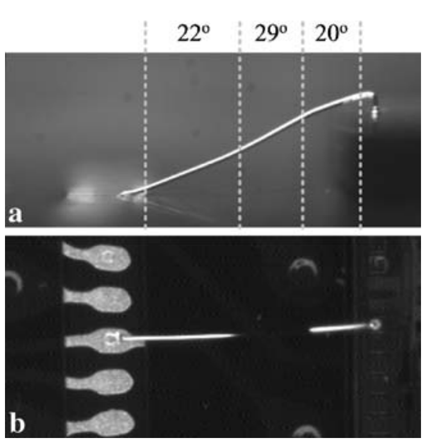


Fig. 20 **a** Side-view image of a sagged wire. **b** Top-view image of the same wire under the properly set up lighting environment

3.4.2.2 Illustration of shifted wire inspection Figure 16 shows the image of a shifted wire and the associated graphs of the inspection result. The two parallel dotted lines in Fig. 16a mark the boundaries of the inspection zone to be inspected. Figure 16b,c are the output graphs, formed by calculating the pixels on the dotted line. These graphs show that the gray levels of the pixels are lower than 100 (pre-defined threshold) in the middle segment, highlighted by the arrows. This means that a broken wire or a shifted wire may occur. The two cases can be distinguished by using the projection method. The dotted rectangle in Fig. 16d marks the region defined for the projection method. The arrow in Fig. 16d indicates the direction of the projection method. Figure 16e is the profile obtained by applying the projection method on the inspection rectangle. There is no abrupt drop-down in the graph, so the image can be classified as a shifted wire.

3.4.2.3 Illustration of broken wire inspection Figure 17 shows an image of a broken wire and the associated graphs of the inspection result. The two parallel dotted lines in Fig. 17a mark the boundaries of the inspection zone. Figure 17b,c are the output graphs formed by calculating the pixels on the dotted line. These graphs show that the gray level of the pixels near the pad, highlighted by the arrows, are lower than 100. The dotted rectangle in Fig. 17d marks the region defined for the projection method and the arrow indicates the direction of the projection method. The profile of the projection shows that there is an abrupt drop-down in Fig. 17e, so the wire under inspection is broken near the pad.

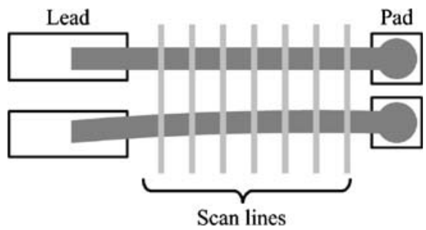


Fig. 21 Illustration of scan lines for sagged wire inspection

3.5 Sagged wire inspection

3.5.1 Algorithm for sagged wire inspection

A good bonding wire will have a similar slope from the highest point to the end (the lead), as shown in Fig. 18a. A sagged wire is a wire which has collapsed in some segment. It is a 3-D type defect for a bonding wire and is hard to be detected in single 2-D image. Under an appropriate lighting environment, we can have such a sagged wire be detected accurately and quickly. The slope of the sagged segment and the associated gray level of the pixels of that segment will be different from a good segment. When the ring type fluorescent light is set up properly, the bonding wire can be highlighted for easy inspection, as shown in Fig. 18b. The ring type fluorescent light is formed by a light tube so that the incident angles of the lights are distributed in some range. The radius of the light tube will affect the range of the incident lighting angle. According to the range of the incident angle, we can calculate the range of the slope of the bonding wire angle that can be highlighted. For example, if the slope of a bonding wire is 22°, the center of the ring type fluorescent light will be set at 46° (by Eq. 1). In Fig. 19, a ring type fluorescent light with a radius of 12 mm is used and is set up above the substrate at a height of 36 mm. The range of the incident lighting angle will range from 39° to 53°. So, if the slope of a bonding wire is less than 18.5° or larger than 25.5°, the bonding wire will not be highlighted in the image.

Normally, a sagged wire will have its slope varying by more than 5°, as shown in Fig. 20a. A sagged wire will not have the whole wire highlighted. Therefore, under a proper lighting environment, we can have a highlighted constant gray-level image for good bonding wires, but a varying gray-level image for sagged wires. As a result, we can have the 3-D type defect of a sagged wire be detected by using a simple 2-D image processing method. We only need to check the gray level of the pixels of every bonding wire which was captured under the properly set up lighting environment. If the gray level of the pixels of a bonding wire located in the segment with constant slope is not constant, then it is a sagged wire, as shown in Fig. 20b.

To check the gray level of the pixels of a bonding wire, we set several scan lines which cross the bonding wire, as shown in Fig. 21. The distance between every two scan lines is set as wide as the diameter of the bonding wire, so that any sagged wire can be readily detected. The critical problem of detecting the 3-D type defect of bonding wires can be effectively reduced to a 2-D type defect by properly setting the light environment. Because not all of the bonding wires on an IC chip will have an exact slope, the light angle should be set up to have the bonding wire reflect most of the light into the camera. When a sagged wire occurs, the gray-level change of the corresponding pixels will be more obvious than others. The algorithm of 3-D bonding wire inspection is described in algorithm 5.

Algorithm 5: Sagged wire (3-D defect) inspection

Input: four images of the bonding wires, an electronic CAD data file of the bonding wires
Output: the index of the sagged wire
Procedure

For i=1 to 4 **do**
Set several scan lines which cross the ball bonding wires in image(i)

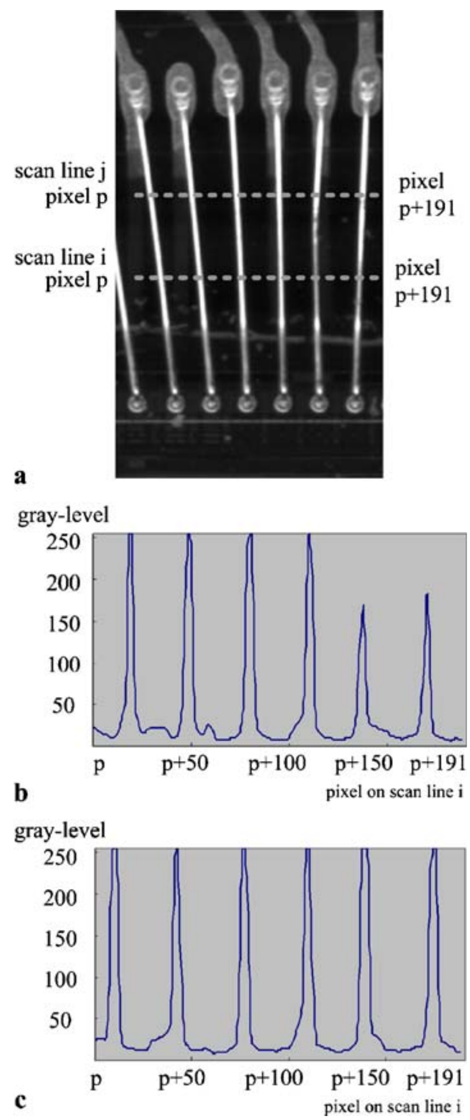


Fig. 22a–c Sagged wire inspection experiment. **a** The two wires on the right of the image are sagged, the others are good wires. **b** The gray level of the pixels of the wires scanned by scan line i. **c** The gray level of the pixels of the wires scanned by scan line j

For j=1 to W **do** /*W is the total number of bonding wires in image(i)*/

For k=2 to L **do** /*L is the total number of scan lines*/

Record the gray level of pixels on scan line (k)
If the difference of the gray level of the pixels between scan line(k) and scan line(k −1) is larger than the pre-defined threshold **then**

Mark wire(j) as a sagged wire
Jump out to check the next wire(j+1)

End if

End for

End for

End for

End procedure

3.5.2 Illustration of 3-D bonding wire inspection

Figure 22a shows six bonding wires in the image; the right-most two are sagged wires while the others on the left are good wires. The two dotted lines in the image represent two sample scan lines for sagged wire inspection. The two scan lines are used for illustrating the gray-level change of the pixels on the bonding wires with and without sagging. Scan line i crosses the segment of the six bonding wires, where the right-most two bonding wires are sagged, see Fig. 22b. Scan line j crosses the segment of the six bonding wires where there are no defects, see Fig. 22c. From the obtained gray level of these wires, we can find out the 3-D type defect of the bonding wire that is the sagged wire by using a 2-D image.

4 Conclusions

In this paper, we have presented a machine vision system for the automatic inspection of wire bonding. A new lighting environment, which avoids the background of the integrated circuit (IC) chip image being extracted, was presented. This lighting environment can also highlight the slope of the bonding wire for inspection purposes. A modified pattern matching method was developed to detect the position of the bonding ball. A set of inspection algorithms was developed to filter out all possible 2-D type errors of a broken wire, lost wire, shifted wire, and shorted wire, and the 3-D type error of a sagged wire. Experimental results showed that the proposed algorithms were very efficient and effective. The inspection speed of this system is fast enough for practical on-line inspection.

Further researches may be focused on integrating this system with an X–Y table robot for on-line inspection [14].

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