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Modal analysis of flip chip for solder bump defect detection

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Abstract Flip chip technology is one of the fastest growing segments of microelectronics packaging because of its ability to satisfy the increasing demands of high input/output density, package miniaturization, and reduced cost. A critical element in the successful application of flip chip technology is the reliability of solder bumps. In this paper, a nondestructive inspection method combining ultrasonic excitation with modal analysis is proposed for flip-chip solder bump defect detection. The signal generator and power amplifier are utilized to drive the capacitive air-coupled ultrasonic transducer to produce continuous ultrasonic waves for exciting the test chips. The vibration velocities of the chips are measured by the laser scanning vibrometer to extract the modal shapes and resonance frequencies. The results prove that the defective chips can be distinguished from the good chip by the modal shapes, and the resonance frequencies of the chips decrease with the increase of the open solder bumps. Therefore, this detection method may provide a new path for the improvement and innovation of flip chip on-line inspection systems.

Introduction

As demands in miniaturization and functionality increases, high-density interconnection and high-number of input/output requirement are indispensable in microelectronics fabrication [1]. Flip chip technology offers a promising solution with excellent electrical and thermal performance owing to its small interconnection resistance and ultra-fine pitch [2]. In flip chip technology, the solder bumps not only provide conventional functions, such as heat dissipation and electrical connection [3], but also help to maintain the precise alignment between the chip and the substrate [4]. Therefore, the reliability of solder bumps becomes a critical element for the successful application of flip chip technology [5].

Current inspection approaches for solder bump defect detection include electrical testing, optical inspection, scanning acoustic microscopy (SAM) inspection, and X-ray inspection [6]. Electrical testing can detect the defects of a short circuit and open circuit [7], but incapable of identifying the intermittent defects such as partial cracks. Optical inspection is convenient for the quality assessment of wire bonded solder bumps [8]. Due to the structure of flip chip, the inner solder bumps are difficult to observe, causing optical inspection almost infeasible. In SAM inspection, a coupling medium between the transducer and the specimen is required for impedance matching [9]. Since the coupling medium may induce defects to solder bumps owing to the effect of fluid impact and corrosion, it is generally inappropriate to immerse the electronic devices into the coupling mediums such as deionized water, oil, and Vaseline. X-ray inspection is a useful tool to isolate and analyze the solder bump defects in a non-destructive way [10]. However, X-ray inspection requires a high degree of operator skill and the equipment is very expensive. Thermal imaging and laser ultrasonic technology are also introduced into solder bump defect detection. Lu et al. proposed a thermal inspection approach based on the pulsed phase thermography for identification of missing solder bumps [11]. Zhang et al. developed a laser ultrasound inspection system to investigate the actual initiation and propagation of solder bump cracks under temperature cycling [12].

In this paper, a nondestructive inspection method using ultrasonic excitation and modal analysis is presented for detecting open solder bumps, which is a typical defect in flip-chip packaging [13].Continuous ultrasonic waves are utilized to excite the test chips. The vibration velocities of the chips are measured by the laser scanning vibrometer. The chip modal shapes and resonance frequencies are extracted based on the velocity data for further analysis. The results prove the feasibility of this method for solder bump defect detection.

Ultrasonic Excitation Methodology

Ultrasonic excitation is a convenient technique for exciting the small structures in modal analysis [14]. In the ultrasonic field, the transmission of ultrasonic waves causes a transient ultrasonic pressure in the medium [15], which can be expressed as

$$p(\boldsymbol{r},t) = P(\boldsymbol{r}) \cos\left[2\pi ft + \varphi(\boldsymbol{r})\right]. \tag{1}$$

Here $\boldsymbol{r}$ is the location vector, t is time, $P(\boldsymbol{r})$ is the amplitude of ultrasonic pressure at $\boldsymbol{r}$, f is the frequency of the ultrasonic waves and $\varphi(\boldsymbol{r})$ is the phase of the ultrasonic waves at $\boldsymbol{r}$. Then an instantaneous energy density $e_f(\boldsymbol{r},t)$ derived from the transient acoustic pressure $p(\boldsymbol{r},t)$ will produce an ultrasonic radiation force on the object located in the transmission direction of the ultrasonic waves [16], which can be written as

$$F_f(\boldsymbol{r},t) = e_f(\boldsymbol{r},t)d_r(\boldsymbol{r})dS = P(\boldsymbol{r})^2 \cos[2\pi ft + \varphi(\boldsymbol{r})] / \rho c^2 \cdot d_r(\boldsymbol{r})dS. \tag{2}$$

Here ρ is the medium density, c is the sound speed, $d_r(\boldsymbol{r})$ is the drag coefficient [17], and dS is the area element in the transmission direction of the ultrasonic waves. Huber et al. utilized the ultrasonic radiation force to excite a MEMS mirror and MEMS gyroscope for modal testing [18]. Kang et al. exploited the ultrasonic radiation force to excite a micro-cantilever for evaluating its dynamic response [19]. It proved the feasibility of using ultrasonic radiation force to excite the microstructures. Therefore, the ultrasonic waves were applied in this work for exciting the flip chips.

Experimental Setup

The daisy-chain flip-chip test chips (Pac2.1, Pac Tech) were employed in the experiments. The chip size was 10×10 mm. There were 184 solder bumps, 90 μm in diameter with a bump pitch of 200 μm, uniformly distributed along the chip edges. As a typical defect in flip-chip packaging, open solder bumps were introduced by removing one to four solder pads from the substrates (PCB310, Pac Tech), as shown schematically in Fig. 1. Then the test chips were bonded to these substrates by reflow soldering process.

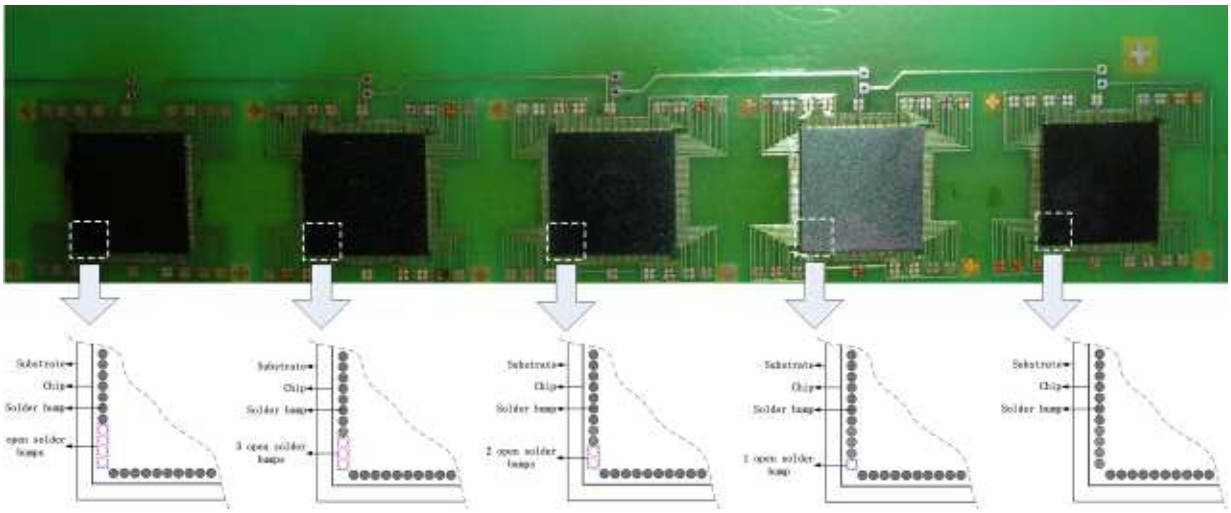


Fig. 1 Schematic diagram of the open solder bump locations

An experimental system for solder bump defect detection was constructed, as depicted in Fig. 2. The signal generator (GEN-M2, Polytec) and power amplifier (HFVA-62, NJFN) were utilized to drive the capacitive air-coupled ultrasonic transducer (CAP3, ULTRAN Group) to produce continuous ultrasonic waves. Then the ultrasonic waves were projected onto the flip chip with an incident angel of 45 degrees for vibration excitation. The substrate of the flip chip was fixed on the vibration isolation table by adhesive tapes. In the experiments, 400 measurement points were distributed uniformly on the chip surface. The vibration velocities of these points were measured by the laser scanning vibrometer (PSV-400, Polytec) with a sampling frequency of 1.28 MHz. The vibrometer operates on the Doppler principle, measuring the frequency shift of the back-scattered laser light reflected from a vibrating point to determine its instantaneous velocity. The chip modal shapes were reconstructed based on the velocity data.

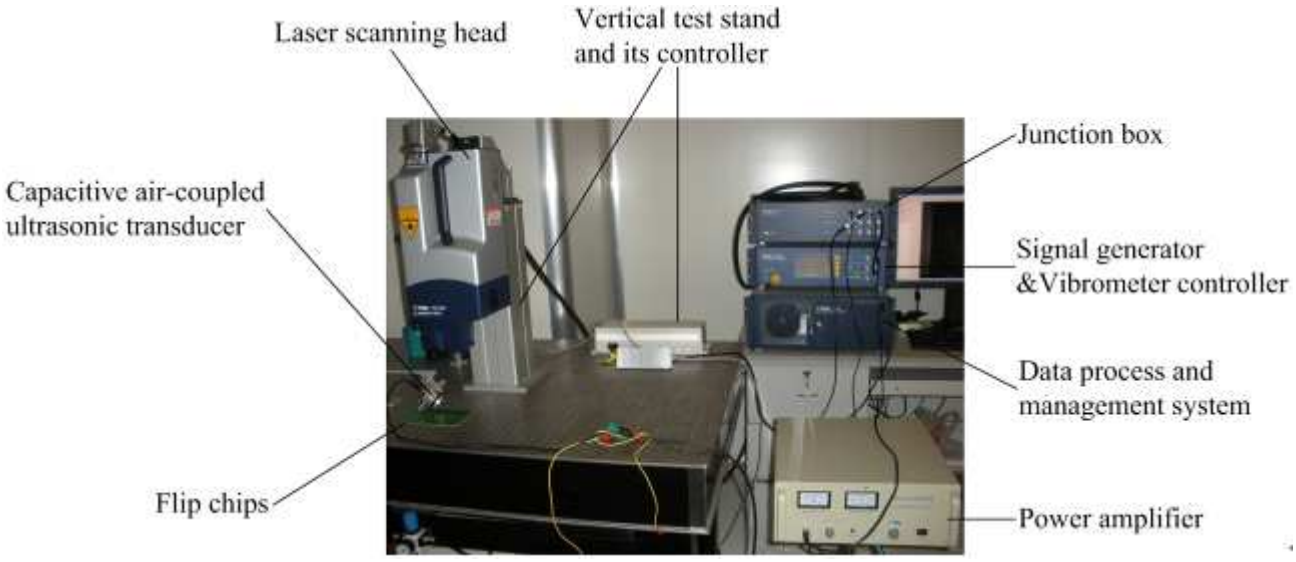


Fig. 2 Experimental system for solder bump defect detection

Results and Discussion

The chip modal shapes are displayed in Fig. 3. The vibration enhanced area of the good chip at the first-order was circular whereas those of the defective chips were elliptical. In regard to the second-order modal shapes, the vibration enhanced area of the good chip was approximately axisymmetric, while those of the defective chips were approximately centrosymmetric.

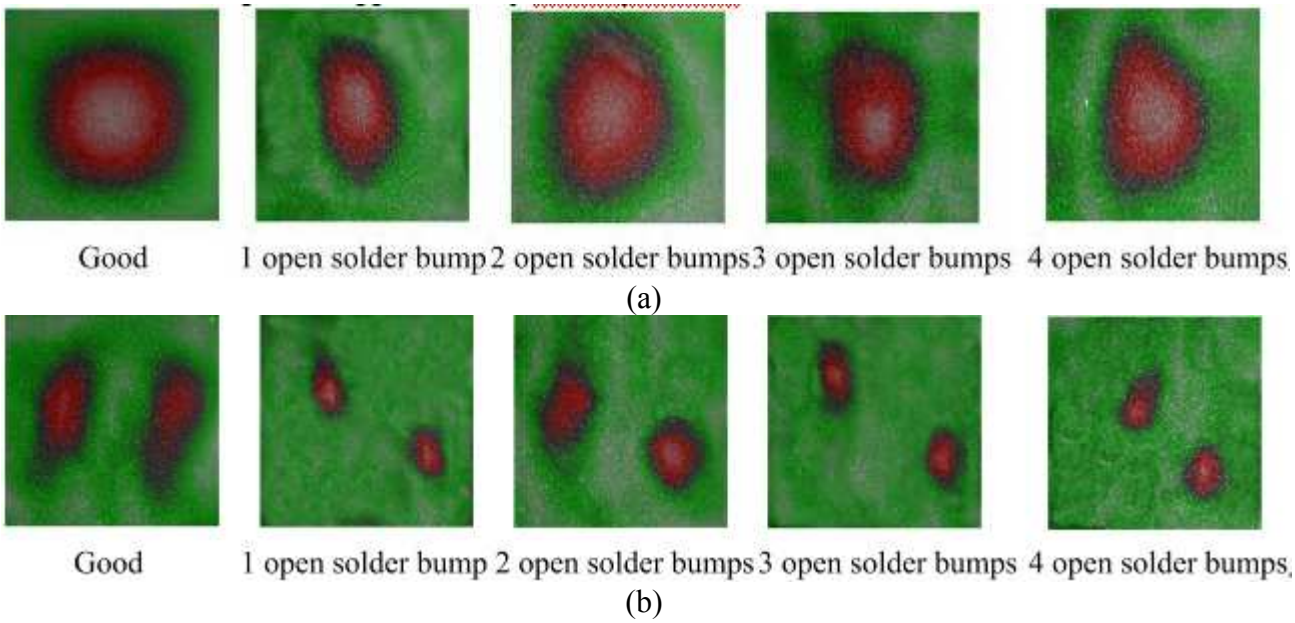


Fig. 3 (a) First-order modal shapes (b) Second-order modal shapes

In order to distinguish the difference in the modal shapes between the good chip and defective chips, an image processing technique was introduced, as shown in Fig. 4. Firstly, the RGB components of the original images were analyzed to obtain the grayscale images of R, G, and B channels. Then the grayscale images were derived from R channel images minus B channel images. To extract the regions of interest (ROIs), the grayscale images were converted to the binary images by thresholding [20], where the white regions represented the ROIs. For the first modal shapes, the aspect ratio for the bounding rectangle of the ROI was calculated. For the second modal shapes, in each ROI of the original image, the characteristic point with maximum velocity amplitude was extracted, and a characteristic angle was obtained. Fig. 5 shows the aspect ratios and the characteristic angles of the modal shape images. The aspect ratio of the good chip was less than those of the chips with open solder bumps, and the characteristic angle of the good chip was smaller than those of the defective chips. Therefore, the defective chips can be distinguished from the good chips by the modal shapes.

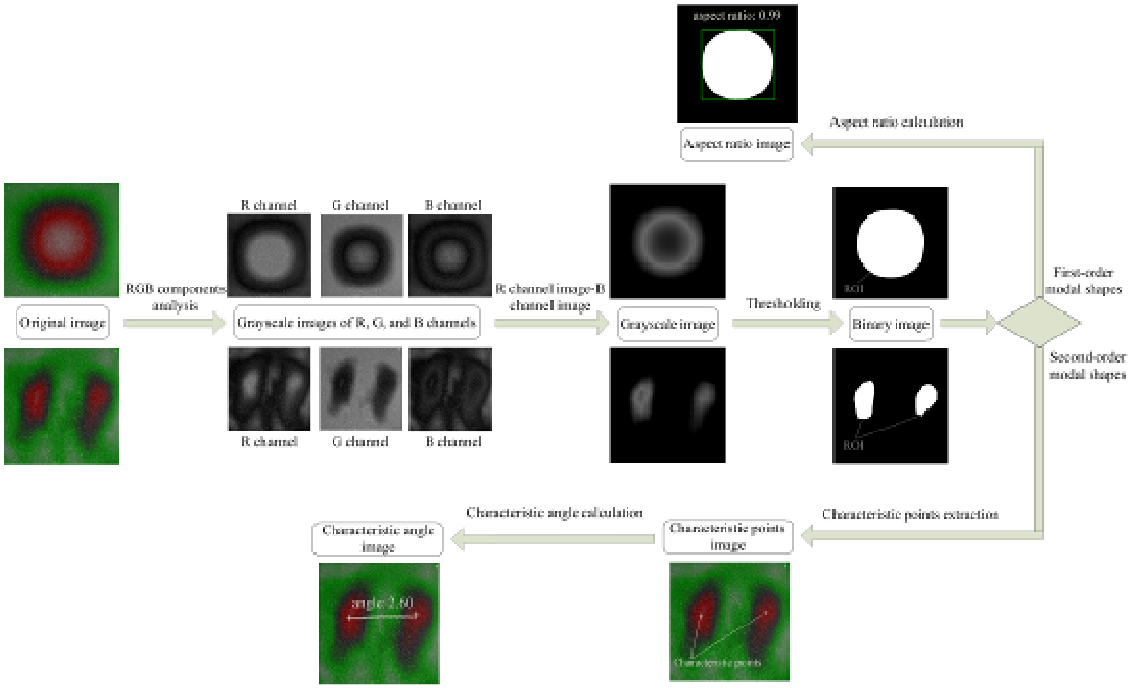


Fig. 4 Flow chart of the image processing

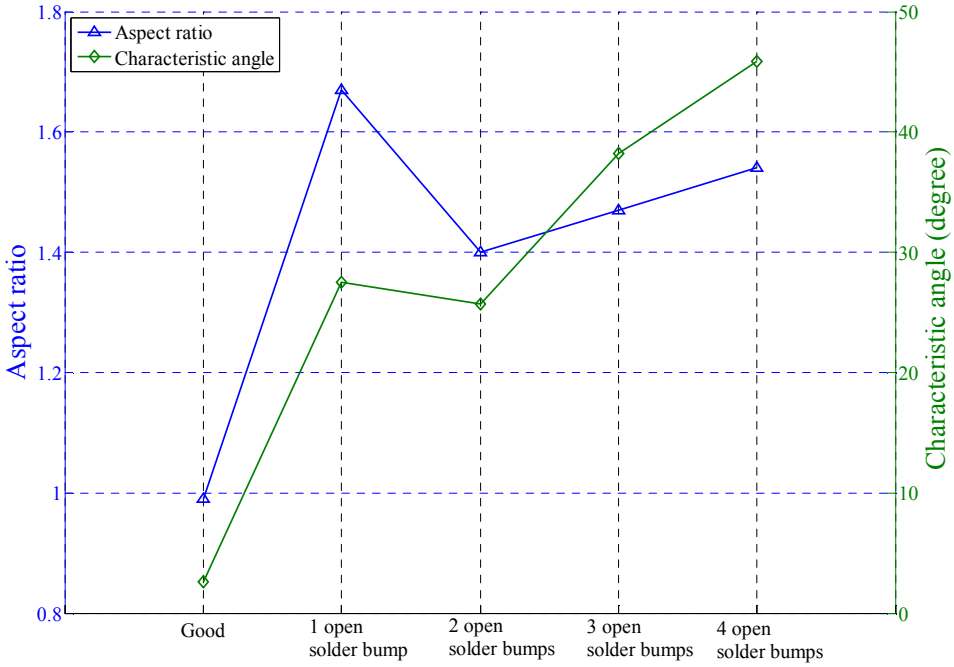
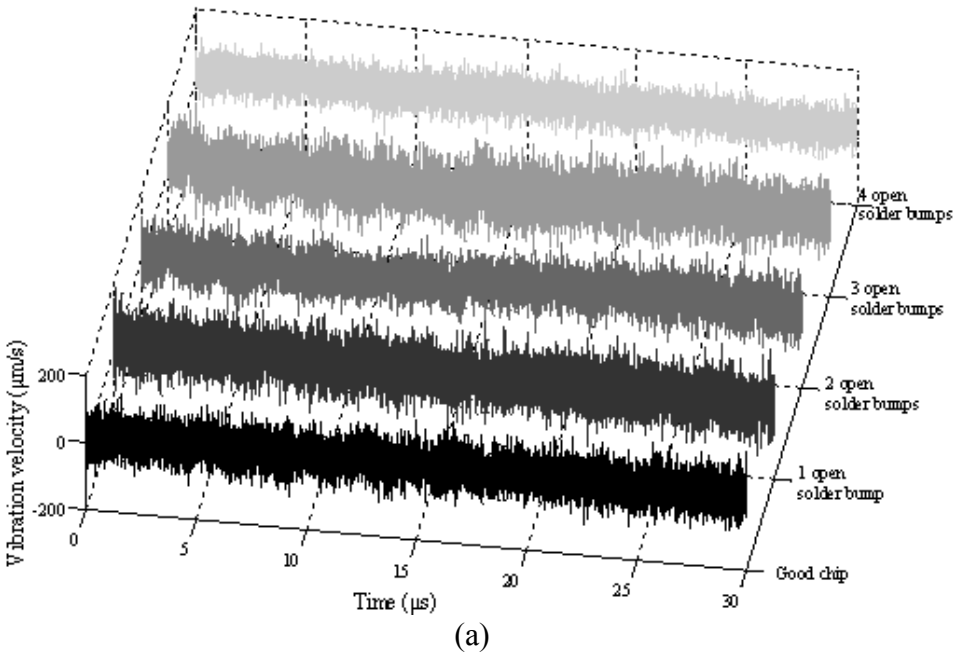
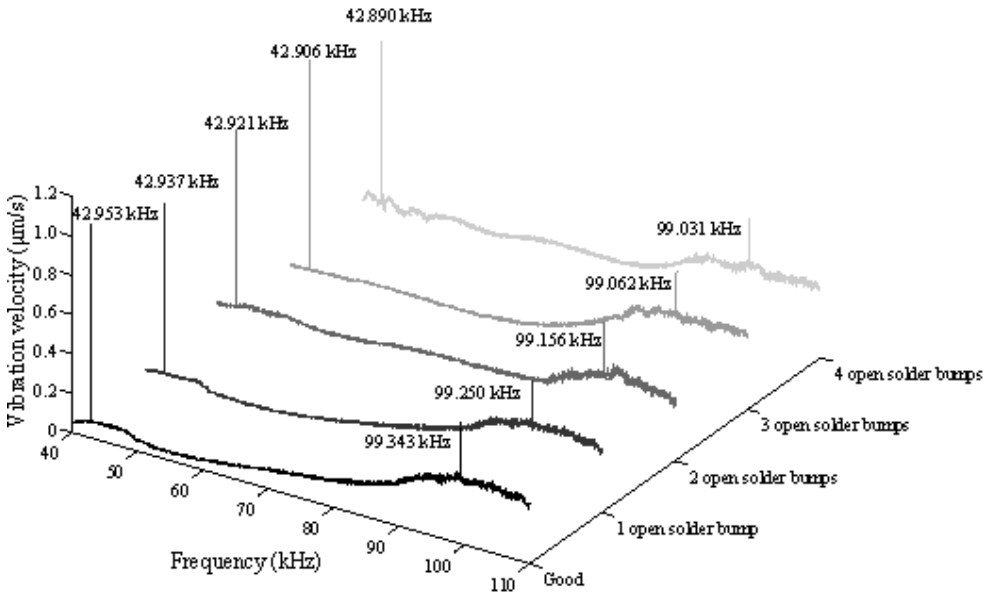


Fig. 5 Aspect ratios and characteristic angles of the modal shape images

The chip resonance frequencies were also investigated through the chip vibration velocities, as shown in Fig. 6. Differences between the good chip and defective chips were difficult to be identified in the time-domain. Thus the time-domain vibration velocities were band-pass filtered (40 kHz-110 kHz) and converted to the frequency spectra. According to $([K]-4\pi^2 f^2\ [M])\{C\}=0$, the resonance frequency f will diminish with the decrease of system stiffness $[K]$ induced by the open solder bumps [21]. As shown in Fig. 6(b), the first-order and second-order resonance frequencies of the defective chips were both smaller than those of the good chip. The chip with more open solder bumps had a lower resonance frequency, meaning that the resonance frequency decreased with the increase of open solder bumps. Furthermore, the decreases between the adjacent resonance frequencies at the second-order were larger than those at the first-order. Therefore, the second-order resonance frequency was probably more sensitive than the first-order resonance frequency for open solder bumps.



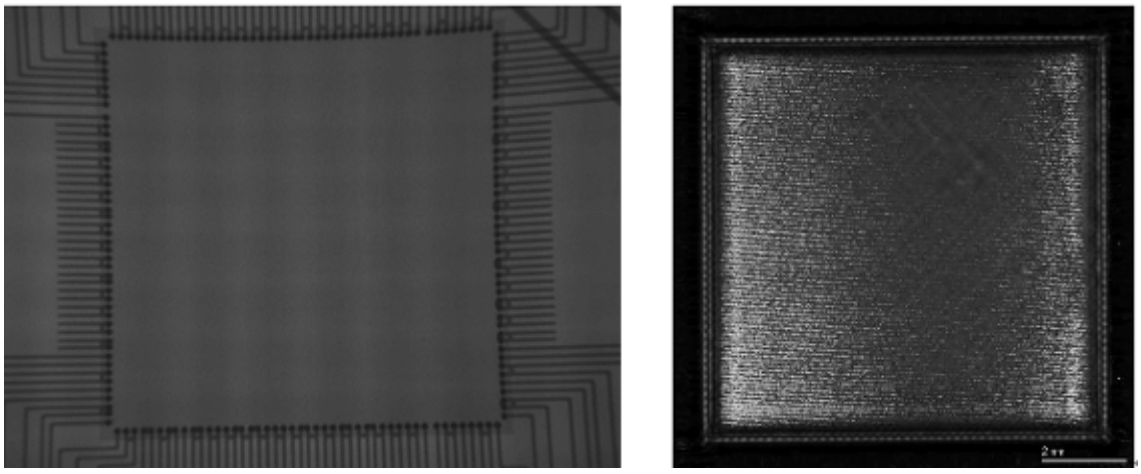
(a)



(b)

Fig. 6 (a) Time-domain vibration velocities (b) Frequency spectra of vibration velocities. There is a discrepancy in the velocity amplitudes between (a) and (b), because the time-domain velocities are the superposition of the frequency-domain velocities on each frequency component.

For comparison, the X-ray inspection (AX8100, Unicomp) and the scanning acoustic microscopy (SAM) inspection (SAM300, PVA TePla) were carried out. The inspection results are shown in Fig. 7. It was difficult to identify the open solder bump in the X-ray image, because the solder pads were obscured by the solder bumps. In SAM inspection, the scattering of acoustic waves at the sample edges would cause the clarity of SAM image to decrease, which made the chip edges fuzzy in the SAM image. Since the solder bumps were situated at the chip edges, the open solder bump was difficult to be revealed by the SAM image.



(a) (b)

Fig. 7 Inspection results of the chip with 1 open solder bump: (a) X-ray inspection (b) SAM inspection

Conclusion

In this paper, a nondestructive inspection method combining ultrasonic excitation with modal analysis is presented for solder bump defect detection in flip chip packaging. The signal generator and power amplifier are utilized to drive the capacitive air-coupled ultrasonic transducer to produce continuous ultrasonic waves for exciting the test chips. The vibration velocities of the chips are

measured to reconstruct the modal shapes and extract the resonance frequencies. The results reveal that the chips with open solder bumps can be distinguished from the good chips by modal shapes, and the resonance frequencies of the chips decrease with the increase of open solder bumps. Therefore, this inspection method may provide a new path for the improvement and innovation of the flip chip on-line inspection systems.

Acknowledgements

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