Development of Real Time/Variable Sensitivity Warpage Measurement Technique and its Application to Plastic Ball Grid Array Package

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Abstract—Far infrared Fizeau interferometry (FIFI) and shadow moiré with enhanced sensitivity (SMES) are developed for real time warpage measurement of microelectronics devices. The methods are implemented in a compact apparatus that is based on a computer controlled environmental chamber. The apparatus combines the two methods to provide unique capabilities of thermally induced warpage measurement with variable sensitivity, ranging from 5.3 to 100 μm. The methods are employed to document warpage of plastic ball grid array packages subjected to various thermal cycles.

Index Terms—Contour interval, far infrared Fizeau interferometry (FIFI), plastic ball grid array packages, shadow moiré with enhanced sensitivity (SMES), thermal cycle, warpage.

I. INTRODUCTION

Warpage of the organic substrate and the assembled package is one of the most critical issues in the second level assembly process of plastic ball grid array (PBGA) packages. The warpage is attributed to a large mismatch of coefficient of thermal expansion (CTE). Several whole-field optical methods have been utilized for warpage measurement of microelectronics components [1]–[3]. They include Twyman/Green interferometry, Holographic interferometry and shadow moiré. The first two provide a sub-micron measurement sensitivity and the third typically provides a measurement sensitivity of 50 μm. As a result, the first two techniques were limited to the small out-of-plane deformation measurement of silicon chips, and the third to the relatively large deformation measurement of printed circuit boards (PCB). This large gap in measurement sensitivity makes the methods less practical for warpage measurement of small organic substrates and PBGA packages.

This research is intended to provide enhanced capabilities of warpage measurement of microelectronics components. Two methods are developed and implemented; they are far infrared Fizeau interferometry and shadow moiré with enhanced sensitivity. Implementation of the methods is given by introducing a compact real time apparatus. The apparatus is based on a computer controlled environmental chamber, which combines the two methods to provide unique capabilities of thermally induced warpage measurement with variable sensitivity, ranging from 5.3 to 100 μm. The methods are employed to document warpage of plastic ball grid array packages subjected to various thermal cycles.

II. FAR INFRARED FIZEAU INTERFEROMETRY

A. Background: Fizeau Interferometry

Fizeau interferometry is a classical interferometry for measuring surface topography of slightly warped specular (mirror-like) surfaces [4]. A practical optical setup using a small inclined incidence is illustrated in Fig. 1. In the setup, an uncoated optical flat is placed near the specimen surface. The optical flat is illuminated by a collimated beam from a monochromatic light source. A portion of the light is reflected from the back surface of the optical flat, while the other portion is transmitted and reflected from the specimen surface. An imaging system collects the light after reflection.

The wavefront from the reference surface (\(W_1\)), which was originally flat, interferes with the wavefront from the specimen (\(W_2\)) to produce a contour map of the \(z\) coordinate of the specimen surface. The \(W\) displacement can then be determined by

\[
W(x, y) = \frac{\lambda}{2\cos\theta} N(x, y)
\]

where \(N\) is the fringe order at each point in the fringe pattern, \(\theta\) is an angle of incidence and \(\lambda\) is the wavelength of the laser light employed. Angle \(\theta\) can typically be small, whereby \(\cos\theta \approx 1\). Then (1) defines the measurement sensitivity as \(\lambda/2\) per fringe order.

Although simple, the application of Fizeau interferometry using visible light has been limited since it requires a specular (mirror-like) surface on the specimen. In addition, measurement sensitivity is a fraction of micron, which is usually too sensitive for typical warpage of microelectronics components. Far infrared Fizeau interferometry (FIFI) was developed to cope with these problems.

B. Far Infrared Fizeau Interferometry

It has been known that the specular component of reflective light increases as the wavelength or the angle of incidence increases [5]. Consequently, a surface regarded as optically
Fig. 1. Fizeau interferometry with small inclined incidence.

rough under visible light can be treated as specular under light with a longer wavelength [6]–[8]. The increase of specular reflection can be explained qualitatively by using the relationship known as the Rayleigh criterion

\[
\frac{4\pi h \cos \theta}{\lambda}
\]

(2)

where \( h \) is the height of the surface irregularities, \( \lambda \) is the wavelength, \( \theta \) is the angle of incidence [5], [8]. The Rayleigh criterion can be used as a measure of effective surface roughness. Theoretically, a surface will become perfectly specular when \( h/\lambda \) approaches zero or \( \theta \) approaches 90°.

In FIFI, far infrared light is employed to decrease the surface requirement. Considering \( h = 10.6 \mu m \) for a CO\(_2\) laser, the relative roughness is reduced by a factor of 20 at normal incidence (\( \theta = 0^\circ \)), compared with a wavelength in the middle of the visible spectrum (green light with 0.5 \( \mu m \)). Consequently, when using far infrared light, the optically rough surfaces under visible light such as the ground surface of silicon, organic substrates, etc., can be tested without any specimen preparation. With \( \lambda = 10.6 \mu m \), the basic sensitivity provided by the method is 5.3 \( \mu m \) per fringe order.

A rough dielectric surface was tested to demonstrate the relaxed surface requirement. The specimen was a float glass ground by a 600 grit grinding paper. The specimen was first adjusted until its surface became parallel to the optical flat. The specimen was then rotated with respect to the \( y \) axis (Fig. 1) and the fringe pattern was recorded. The straight fringes shown in Fig. 2 represent a linear out-of-plane displacement caused by rotating the specimen. Excellent fringe contrast with high signal-to-noise ratio was achieved. Roughness tolerance of the specimen surface is evident from the fringe pattern.

III. SHADOW MOIRÉ WITH ENHANCED SENSITIVITY

A. Background: Shadow Moiré with Constant Sensitivity

Shadow moiré has evolved as the moiré method most widely chosen for out-of-plane measurements. The most practical shadow moiré arrangement is illustrated in Fig. 3, utilizing oblique illumination and normal viewing [4]. In the method, a real reference grating of pitch \( g \) is located in front of a specimen and it creates moiré fringes by interacting with its shadow on the specimen. The grating is comprised of black bars and clear spaces on a flat glass plate. A light source illuminates the grating and the specimen, and the camera receives the light that is scattered in its direction by the specimen surface. The specimen surface is usually prepared by spraying it with a thin film of matte white paint for uniform diffusion.
Normal viewing is preferred to avoid foreshortening and distortion of the image, even though measurement sensitivity can be increased with oblique viewing. With this arrangement, where the source and the camera lie at the same distance \( D \) from the plane of the specimen, the relationship between \( W \) and fringe order \( N \) is

\[
W = \frac{g}{\tan \alpha + \tan \beta} N = \frac{gL}{D} N
\]  

where \( D \) is the distance between the camera and the light source, and \( W \) and \( N \) apply to each \( x, y \) point in the field. It is important to note that although incidence and viewing angles \( \alpha \) and \( \beta \), respectively, vary across the field, the sum of their tangents is a constant, which provides a constant sensitivity across the field. Equation (3) defines the measurement sensitivity as \( gL/D \) per fringe order. With a given reference grating of pitch \( g \) the basic sensitivity can be increased by increasing the distance \( D \).

The above explanation assumes rectilinear propagation of light; the assumption is reasonable when the gap \( W \) is small compared to the grating self-imaging distance \( g^2/\lambda \) (also known as Talbot distance) [4]. In practice, the sensitivity of shadow moiré is limited by an undesired diffraction effect from the reference grating, which decrease fringe visibility or contrast. A reference grating of 20 lines/mm (500 lines/in) has often been used as a practical upper limit.

### B. Enhancement of Contrast and Sensitivity by Digital Image Processing

In shadow moiré, fringe contrast and visibility decreases rapidly as the frequency of the reference grating increases. A simple but robust digital image processing scheme was developed to enhance the fringe contrast of shadow moiré fringes when using the reference grating with a frequency near the practical limit. The scheme also provides two-fold sensitivity enhancement.

In the idealized case of a reference grating with equal bar and space width, the (averaged) intensity distribution of shadow moiré fringes is triangular [4]. The intensity distribution can be expressed by a Fourier cosine series as

\[
I_0(x, y) = I_m(x, y) + \sum_{n=1}^{\infty} C_n(x, y) \cos \left[ n\phi(x, y) \right]
\]  

where

- \( I_0 \) intensity distribution;
- \( I_m \) mean intensity;
- \( C_n \) coefficient of the harmonic series;
- \( \phi \) angular phase information;
- \( (x, y) \) all the points in the \( x, y \) plane of the object and the shadow moiré pattern;
- \( \phi \) fringe order \( N \) at each point of the pattern; by

\[
\phi(x, y) = 2\pi N(x, y).
\]  

A phase (or fringe) shifted pattern can be recorded with a constant increment of the phase. This can be accomplished by moving the reference grating in the \( z \) direction to increase \( W \) uniformly throughout the field (see Fig. 3). By (3), \( N \) is changed by one fringe order when \( W \) is increased by \( g \). Accordingly, a phase-shifted pattern can be obtained by shifting the reference grating by a fraction of its pitch.

The intensity distribution of a phase-shifted pattern \( I_s \) can be written as

\[
I_s(x, y) = I_m(x, y) + \sum_{n=1}^{\infty} C_n(x, y) \cos \left[ n\phi(x, y) + \frac{2\pi}{k} \right], \quad n = 1, 2, 3, \ldots
\]  

where \( k \) is an arbitrary value greater than 1. By subtracting these intensities, one obtains the intensity distribution \( I_r \) as

\[
I_r(x, y) = I_0(x, y) - I_s(x, y) = 2 \sum_{n=1}^{\infty} C_n(x, y) \sin \left[ n\phi(x, y) + \frac{\pi}{k} \right] \sin \left[ \frac{n\pi}{k} \right].
\]  

The idea of subtraction can be found in [9]–[12]. Since \( C_n \neq 0 \) and \( \sin(n\pi/k) \neq 0 \), the phase values \( \phi(x, y) \) of the points where the condition \( I_r(x, y) = 0 \) is satisfied can be expressed as

\[
\phi = m\pi - \frac{\pi}{k} = \pi \left( \frac{mk - 1}{k} \right), \quad m = 0, \pm 1, \pm 2, \ldots
\]  

Then, by (5), the fringe orders where \( I_r(x, y) \) is zero are

\[
N(x, y) = \frac{mk - 1}{2k}, \quad m = 0, \pm 1, \pm 2, \ldots
\]  

The \( x, y \) points where \( I_r(x, y) = 0 \) are determined by first taking the absolute value \( |I_r(x, y)| \), and then truncating and binarizing the function near \( |I_r(x, y)| = 0 \).

The steps in the method are represented in Fig. 4. The intensity distributions of \( I_0 \) and \( I_s \) are illustrated in Fig. 4(a), where the dashed curve represents the intensity of the phase-shifted pattern. Their difference is plotted in Fig. 4(b) and the absolute values of the difference in Fig. 4(c). This function is truncated near zero intensity and binarized to obtain the sharpened intensity distribution in Fig. 4(d). Narrow black fringe contours are generated along the loci of \( x, y \) points where \( |I_r| \) is zero, where the second subscript denotes binarization.

The result is a sharpened contour map with high contrast that has twice as many contour lines as the number of fringes in the initial pattern. The sharpened contours occur at the
crossing points of the two graphs, where the intensities of the two patterns are equal. Consequently, any noise or other factor that affects the two patterns equally has no influence on the locations of the crossing points [12]. Note that the fringe orders of the crossing points are separated by 0.5.

The resultant contour map is interpreted in the normal way, where the contour order $N^*$ is proportional to the displacement. Since rigid body displacements are unimportant, $N^*$ can be assigned arbitrarily to any contour as illustrated in Fig. 4(d). Then, the resultant pattern represents $W$ displacement by

$$W = \frac{gL}{2D^3}N^*.$$  \hfill (10)

The scheme is illustrated in Fig. 5 on a whole-field basis. The original and the corresponding phase-shifted patterns are shown as $I_o$ and $I_s$. The sequence in Fig. 5 continues with the pattern [referring back to Fig. 4(c)] obtained by subtracting these intensities and taking the absolute values of the resultant intensities. The last pattern is the same distribution after truncation near $I_r = 0$ and binarization. The result is a pattern of highly sharpened fringe contours with twice as many contours as those in $I_o$ and $I_s$, Enhancement of fringe visibility is evident.

**IV. EXPERIMENTAL APPARATUS FOR REAL TIME MEASUREMENT**

Far infrared Fizeau interferometry (FIFI) and shadow moiré with enhanced sensitivity (SMES) are combined in a compact and practical apparatus. The apparatus is based on a computer controlled environmental chamber. The chamber has a heating/cooling rate of 0.5 °C/s. and an operating range of −50 °C to 300 °C. Fig. 6 illustrates the apparatus. The specimen is mounted on a special fixture (not shown) located inside the environmental chamber, which in turn is connected to flexible shafts. The flexible shafts permit the necessary adjustment of specimen and optical elements for phase (or fringe) shifting while operating the environmental chamber.

The optical configuration shown in Fig. 1 was implemented for the FIFI system, where an incident angle of $\theta = 2^\circ$ was used. The optical flat and the collimating lens were mounted on a specially designed circular port on the environmental chamber, which allowed easy replacement of the specimen without readjusting the optical system. In the optical configuration, laser light from a CO$_2$ laser is reflected by a silicon mirror and expanded by a beam expander, as illustrated in the insert of Fig. 6. The diverging light illuminates the collimating lens. The light reflected from the optical flat and the specimen surface is collected by the same lens and it is focused on a thermal imaging CCD camera through an imaging lens.

All the optical elements were fabricated from ZnSe. Its transmission spectrum is 0.54–18.2 μm. The large transmission spectrum allowed using a visible laser diode for initial alignment of the optical elements as infrared light was not visible. A specially designed laser diode was mounted on the head of the CO$_2$ laser (see the insert of Fig. 6) and it was aligned with the CO$_2$ laser. After tuning the optical system with the laser diode, the output power of the CO$_2$ laser was controlled by a
D/A converter, installed in a PC, through a universal controller. The fringes were visible on a TV monitor at this point and fine adjustments were made while observing the fringe patterns. The system provided the measurement sensitivity of 5.3 μm per fringe order.

The configuration shown in Fig. 3 was implemented for the SMES system. Illumination was conducted by optical fibers from a white light source, which lies at the same distance from the plane of the specimen as the camera. Light illuminates the replaceable reference grating and the specimen (not shown) through the side window, and the images are obtained through a top window. This configuration allows the specimen to be kept in the middle of the chamber to ensure a uniform temperature distribution. The imaging system is comprised of a high-power zoom lens and a CCD video camera.

The optical fiber illuminator was fixed at a discrete location along the track, providing $D = 2L$ (see Fig. 3). Recalling (3), this arrangement provides a sensitivity of $g/2$ per fringe order with a given a reference grating of pitch $g$. The reference gratings with two different pitches (50 and 100 μm) were used in the system. With the two-fold sensitivity enhancement by the digital image processing, the measurement sensitivity provided by the system was 12.5, 25, and 50 μm per fringe order.

V. APPLICATIONS

A. Flip-Chip Plastic Ball Grid Array Package

The warpage of flip-chip plastic ball grid array (FC-PBGA) packages is produced by a CTE mismatch between the chip and the organic substrate through a coupling provided by an underfill layer, as illustrated in the insert of Fig. 7. In a high performance FC-PBGA package where a heat sink is usually required, the warpage as well as the absolute displacement of the top silicon surface becomes important design parameters for an optimum thermal solution, especially when nonconductive interstitial materials between the heat sink and the silicon are employed. If the silicon warps and displaces in the direction normal to the surface during operation, nonuniform distribution of apparent interface pressure over the interstitial materials will develop, producing nonuniform thermal conductance [13].

The FIFI system was employed to measure warpage of the front surface of a FC-PBGA package as a function of temperature. In the package, a silicon chip (6 mm × 6 mm) was mounted on an organic substrate (30 mm × 30 mm). The resultant fringe patterns are shown in Fig. 7, where the insert indicates the region viewed by the FIFI system and the contour interval was 5.3 μm per fringe order. It is important to note that roughness tolerance afforded by FIFI made it possible to obtain the fringe patterns without any surface preparation. It is also important to note that the fringe patterns from the chip and the substrate were recorded from a single experiment, although the surfaces of the silicon and the substrate were not located in the same plane.

The out-of-plane displacements were extracted from the fringe patterns using (1) and the results are plotted in Fig. 8. The dotted line represents the relative out-of-plane displacements of the chip (between points A and B in Fig. 7) and the dashed line represents the relative out-of-plane displacements of the substrate (between points B and C in Fig. 7). As temperature increased, the warpage of the chip and the sub-
substrate decreased. The chip became flat at the underfill curing temperature of 165 °C. As temperature increased further, the direction of warpage became opposite due to the higher expansion rate of the substrate. This opposite bending is extremely important for the second level assembly process and it will be discussed later.

The total absolute movement of the chip center is the sum of the relative warpage of the chip and the substrate. The solid line in Fig. 8 represents the total displacements. The magnitude change over room to 100 °C is approximately 40 μm, which is a significant portion of the thickness of typical nonadhesive type interstitial materials. Although the total displacement is reduced after the package is assembled to a PCB motherboard, this movement could significantly affect the thermal performance of the package if a heat sink is rigidly fixed on the motherboard or an enclosed cooling system is employed. The effect of the nonuniform pressure distribution on the thermal performance of the package is under investigation and the results will be reported in future publications.

As mentioned earlier, if the bottom side of the package warps during the second level assembly, the height of the solder balls can vary from the center to the edge. This effect was documented by the SMES system. The same package used in the previous experiment was tested, but the warpage of the backside with metal pads was documented. The results are shown in Fig. 9, where the pitch of the reference grating was 50 μm and the digital image processing was implemented to provide a contour interval of 12.5 μm per fringe order. The maximum relative warpage of the center was determined and the results are plotted in Fig. 10. The results show a similar behavior to the chip warpage seen in Fig. 8, which confirms a high coupling through the underfill layer.

The \( W \) displacement at reflow temperature (200 °C) was extracted from the pattern in Fig. 9 and the displacements along the diagonal (upper-right to lower-left) are plotted in Fig. 11. Assuming the PCB motherboard does not warp during the second level assembly, the height of the center solder ball can be shorter than the edge solder ball by 50 μm. Considering a typical solder ball height of 0.5 mm for 1 mm ball pitch, the height variation can be greater than 10% since the motherboard can actually warp during the assembly process.

B. Wire-Bond Plastic Ball Grid Array Package

The wire-bond plastic ball grid array (WB-PBGA) package is the most widely used PBGA package. In the package, an active chip is first die-bonded to the pad on an organic substrate and the IC’s are connected to the bond fingers on the substrate. The device is then overmolded by a plastic molding compound (PMC) to form the final package, as illustrated in the insert of Fig. 12.

The WB-PBGA package is not hermetically sealed, and thus the PMC and the organic substrate absorb moisture while
The package is in storage. The absorbed moisture is usually condensed at the interfaces. When the package is heated rapidly in a reflow oven, the moisture vaporizes and produces high pressure, which cracks the package; this phenomenon is known as the popcorn effect [14]. The SMES system was employed to document this effect.

The specimen was a 29 mm × 32 mm WB-PBGA package, with 289 I/O interconnections. The results obtained from shadow moiré are shown in Fig. 12, which represent the warpage of the substrate side of the package with a contour interval of 50 μm per fringe order. The sensitivity used in this experiment was four times lower than one used in the previous experiment.

VI. CONCLUSION

A unique experimental apparatus, combining far infrared Fizeau interferometry and shadow moiré with enhanced sensitivity, was developed for real-time warpage measurement of microelectronics components. The combined technique provides unique capabilities with variable sensitivity, ranging from 5.3 to 100 μm. The technique was used to document warpage of PBGA packages subjected to various thermal cycles. The variable sensitivity and roughness tolerance provided by the technique make it ideally suited to warpage measurement of a wide range of surface mount components and assemblies.

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REFERENCES

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