Measuring Die Tilt Using Shadow Moiré Optical Measurements; New Techniques for Discontinuous and Semi-Reflective Surfaces

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Abstract

When dealing with production of Flip Chip Packages in semiconductor packaging, the angle between the die and package substrate is critical for maintaining product yield and reliability. Current outgoing quality checks for die tilt can be time consuming to measure heights via point to point measurement techniques. Existing die tilt measurement approaches can also have reproducibility issues from user to user.

Shadow moiré technology is a full field optical inspection technique commonly used for flatness characterization in the semiconductor industry, particularly at elevated temperatures. Two limitations to shadow moiré apply when discussing outgoing QC of die tilt: 1) shadow moiré requires a diffuse reflective surface for measurement; 2) shadow moiré is unable to measure sudden step heights.

This paper discusses applications techniques and real world examples to overcome or mitigate the limitations of shadow moiré technology and use this full field and high speed measurement technology to measure die tilt. Using shadow moiré for this measurement technology can reduce measurement and user time as well as improve consistency of measurements from user to user. As shadow moiré tools are often used for at temperature flatness measurements, this added application can reduce the number of different measurement tools needed in QA labs.

Key words

3D packaging, Die Tilt, Flip Chip, Warpage

I. Introduction

Consolidating metrology tools in FA, QA, and R&D labs is helpful to save on both lab space and capital equipment costs. Shadow moiré is an optical phenomenon that dates back to the 1940s [1]. Shadow moiré technology inherently has limitations when dealing with sudden changes in height or step heights. Some approaches to overcome step height limitations have been presented [2], but a widely accepted approach to working with shadow moiré on discontinuous surfaces has not been implemented in the common use of this technology for measuring microelectronics sample warpage over temperature. Given the restrictions in interpretation of sudden step heights in shadow moiré, discontinuous surfaces are typically not considered at the same time. However, even without absolute height measurements between two planes, in a shadow moiré system, two separate planes still have a common reference plane defined by the shadow moiré grating.

This paper discusses approaches to get useful information, in the form of surface topography or angle relative to another surface, from shadow moiré data taken between two step heights. Specifically, exposed die samples are investigated as a real world example using this approach. Die surfaces tend to demonstrate highly specular light reflection, which can challenge white light optical metrologies. As a corollary, technology developments dealing with camera bit depth and shadow moiré wrapping algorithms are presented.

II. The Issue of Die Tilt and Metrology

This paper does not focus on reasons to measure the tilt or angle of a die or similar surfaces. The focus of the paper is one of methodology. However, the necessity for managing die tilt is mentioned in numerous other publications, not limited to applications such as substrate-on-chip packaging, solder attachment of large power dice, QFN packaging, etc. [3] – [5].

Focus for this discussion is placed on the shadow moiré technique and extending shadow moiré applications for die tilt or discontinuous surface measurements. Other techniques for measuring the tilt of a die relative to a surrounding substrate are available in the industry. Reference [6] covers one such method, using an optical non contact scanning probe system.

III. Shadow Moiré and Discontinuous Surfaces

Early shadow moiré, prior to any phase stepping technology, was based on counting transitions of dark and light fringes. The geometry of shadow moiré allows calculation of a specific height associated with this same fringe. As in Figure 1, the relative height between A and B can be found by multiplying fringe count by the height of each fringe, "Fringe Value", here assumed to be 250 µm/fringe.

$$\Delta Z = 6\, fringes * \frac{250\mu m}{fringe} = 1.5mm \qquad (1)$$

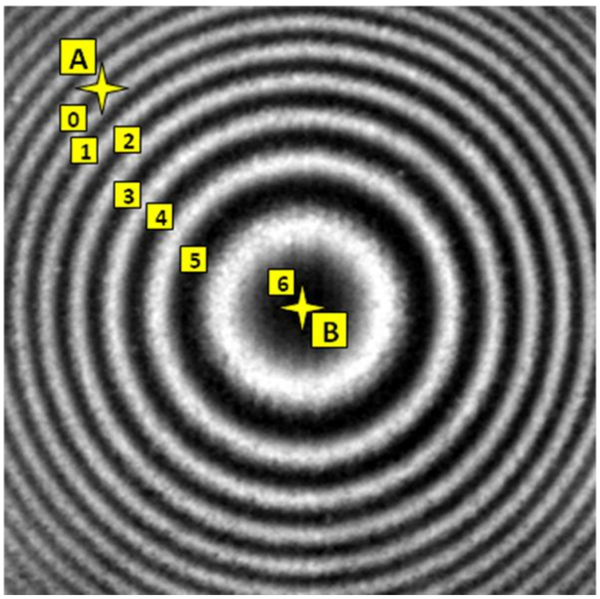

Figure 1. Shadow moiré intensity image

Inherent to this approach is the limitation that transitions between each fringe must be counted along a path. Therefore, very steep slopes or sudden changes in height loose the count or order of the fringe. As a general rule changes greater than one fifth of the measurement Fringe Value between two adjacent pixels can start to introduce issues. This translates to a maximum measurable slope of the surface of approximately 0.2, which is equivalent to an angle of 11.3°. An example with height on the Y axis and light intensity values along a line on the X axis in Figure 2 and Figure 3.

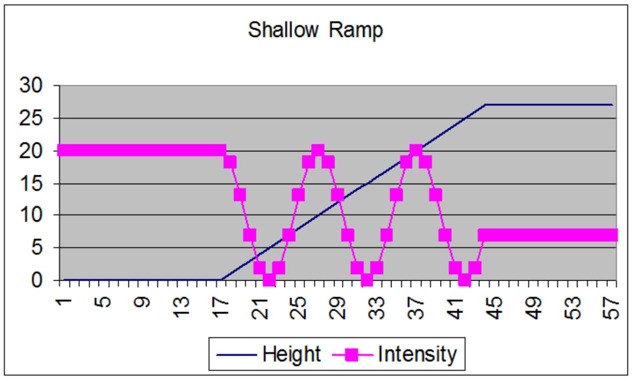

Figure 2. Shallow Ramp, no problem for shadow moiré

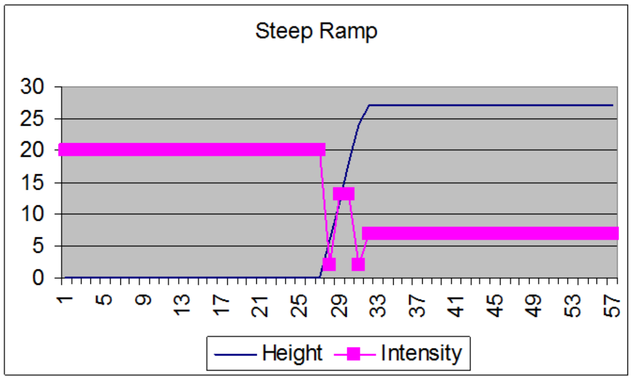

Figure 3. Steep Ramp, problematic for shadow moiré

This limitation of steps heights leads to users ignoring discontinuous surfaces that cannot be connected by shadow moiré fringe lines during measurement. However, two surfaces with an unknown step height still have a common reference plane in the form of the shadow moiré grating. Methods to extract the relative tilt between two separate planes taken in the same measurement area are discussed in the next section.

IV. Shadow Moiré on Discontinuous Surface Implementation

Consider the camera image from a shadow moiré measurement on a real world sample, as seen in Figure 4. This zoomed in section of measurement shows the topside of a component with two exposed die surfaces. Traditional methodology with shadow moiré allows warpage measurement of each die flatness, as well as flatness of any surrounding substrate area from a single measurement.

Each data set is cropped from the image and processed separately, each on its own reference plane. However, shadow moiré can also be used to show the warpage or shape of one surface on the least squares fit (LSF) reference plane of a completely separate surface.

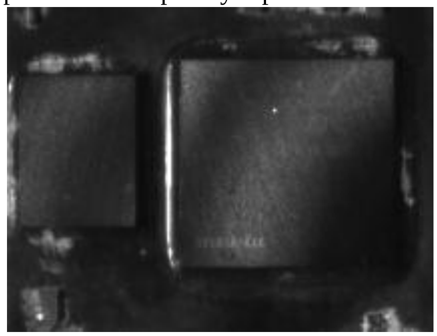

Figure 4. Exposed die shadow moiré image

Consider the left die in Figure 4. Typical use of shadow moiré can show the warpage of this die on a LSF reference plane, made from the same die surface. Figure 5(a) shows the die warpage on its own reference plane. However, the reference plane from the data set can also be extracted from the die surface on the right or the surrounding substrate as shown in Figure 5(b). The common reference of the shadow moiré grating between the different surfaces makes this possible.

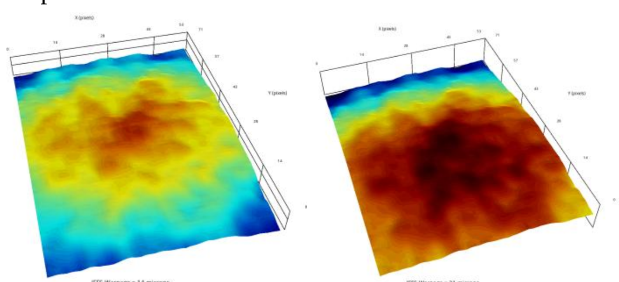

Figure 5.(a) LSF die warpage (b) tilted die warpage

In shadow moiré data, the tilt of any surface is arbitrary to the shadow moiré grating, but given the common grating reference, relative difference in tilt can still be extracted. Figure 6(a) and (b) show the a 1st order fit of the left and right die, respectively, relative to the shadow moiré grating. Each plane by itself adds no value and is purely a byproduct of test setup.

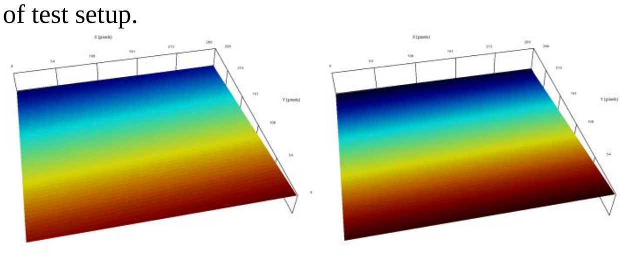

Figure 6.(a) left die plane (b) right die plane

However, if we subtract the two reference planes from one another we now have the relative tilt between the two die surfaces, as in Figure 7. Subtracting Figure 7 from Figure 5(a) then yields our left die warpage, tilted relative to the right die plane in Figure 5(b).

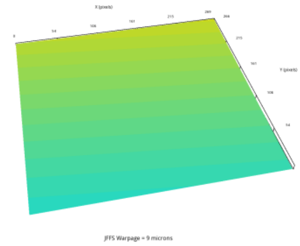

Figure 7. Relative tilt between left and right die

The same approach can be taken when dealing with a single die and surrounding substrate. Again, a common use for shadow moiré and the discussed approach is to extract an angle of a die surface, represented graphically in Figure 8.

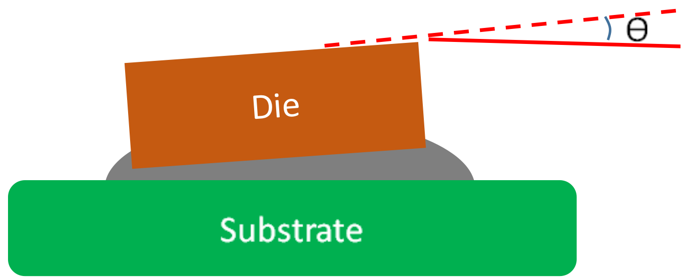

Figure 8. Illustration of tilted die on substrate

A single die flip chip is used as a real world example. In order to validate our approach with shadow moiré a full 3D rendering of our sample is shown in Figure 9 using Digital Fringe Projection (DFP) as our measurement technique. DFP is a complimentary technique to shadow moiré that can measure discontinuous surfaces. DFP is also a viable solution for die tilt. However, measurement resolution, throughput, and field of view are less favorable compared to shadow moiré, thus DFP is not the focus of this discussion. In this case the sample is also painted to improve measurement resolution.

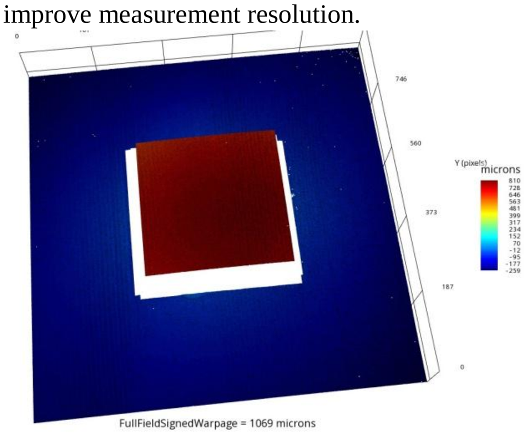

Figure 9. DFP measurement of flip chip

The same concepts with relative tilt can be used to plot the die shape relative to the surrounding substrate. The intermediate steps have already been discussed, thus just the final result is shown in Figure 10.

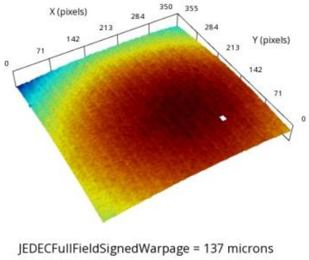

Figure 10. Die Warpage Relative to Substrate Plane

In this case the level of warpage of the die does raise interesting questions about how die tilt is calculated by other techniques. If we only consider the four corners of the die, warpage can affect the measured angle. First, die tilt should be better defined and this topic returned to later.

V. Die Tilt Calculation

Die tilt or die angle is taken by subtracting the Z height of data points from opposite corners of the die and taking the maximum absolute value.

$$Z_{Diff} = \max\left(\left(abs(Z_{TL} - Z_{BR}), abs(Z_{TR} - Z_{BL})\right)\right) \qquad (2)$$

where, Z_{TL} = height value in the top left corner of the die; Z_{BR} = height value in the bottom right corner of the die; Z_{TR} = height value in the top right corner of the die; Z_{BL} = height value in the bottom left corner of the die; then,

$$Die\ Tilt = sin^{-1}\left(\frac{Z_{diff}}{L}\right) \qquad (3)$$

where L = distance diagonally across the die. As needed L can be calculated out of the Akrometrix software using:

$$L = \sqrt{((pixels\ in\ x)^2 + (pixels\ in\ y)^2)} * LRES \qquad (4)$$

where LRES is a software setting converting pixels to mm.

VI. 12 Bit Shadow Moiré and Floating Point Phase

Shadow moiré, like many optical metrologies, has optimal resolution when the measured surface is diffusely reflective of visible light. As such, samples that are not inherently diffusely reflective of light are first prepared with a matte white coating. This point is raised here for two reasons. Firstly, die surfaces are inherently specular. The level of specularity varies from one die surface to another. Secondly, a metrology requiring added sample coating would be less favorable, given that test samples would likely remain for production use. Current shadow moiré technology can measure many die surfaces, as some specularity is acceptable so long as some light hits the surface and returns to the camera.

Recent technological developments in shadow moiré metrology, namely "12 bit shadow moiré" and "floating point phase", can be used to improve measurement resolution on more highly specular die samples. While this improvement does not cover every application, it does expand the range of applications that can hold to customers individual accuracy needs. Traditional measurement data was considered as 8 bit, 0-255, grayscale values. Through improvements in software and camera imaging, shadow moiré data is now processed as 12 bit, 0-4095, grayscale values, allowing for more highly specular and darker samples to be measured accurately. Floating point phase shadow moiré calculations compliment this expanded data set by limiting data rounding, to produce the most accurate data points. As an example, a polished 300mm wafer was measured, being a realistic surface finish for a die surface. Figure 11(a) shows noisier and partially lost data on a polished wafer surface, using 8 bit shadow moiré. Figure 11(b) shows an improved measurement without lost data and improved resolution taken with 12 bit shadow moiré.

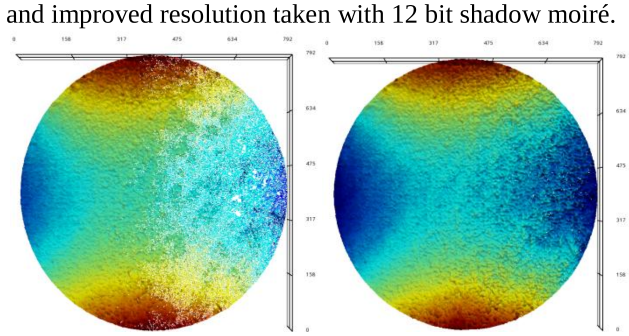

Figure 11.(a) 8 bit measurement (b) 12 bit measurement

It should be noted that this improved approach does not cover every surface finish. A pure mirror still cannot be measured by shadow moiré or fringe projection techniques.

VII. Advantages of Using Shadow Moiré

This paper focuses on extending the uses of a shadow moiré measurement tool. However, when pursuing the measurement of die tilt via shadow moiré, another inherent advantage of the technique was identified. Measuring on a point to point basis, if focused on 4 corner points of the die and a surrounding board location, the warpage of the die could play a noticeable role in the perceived angle of the data set. However, with a full field data set a user can choose to include or exclude the warpage of the die surface from the die angle calculation. To explain further, consider the tilted die surface shown in Figure 12(a). If we consider only the 4 corners using equations (2)-(4) the die angle is calculated as 0.083°. Whereas, after removing the warpage and leaving only a 1st order plane fit of the die surface the angle changes to 0.112°.

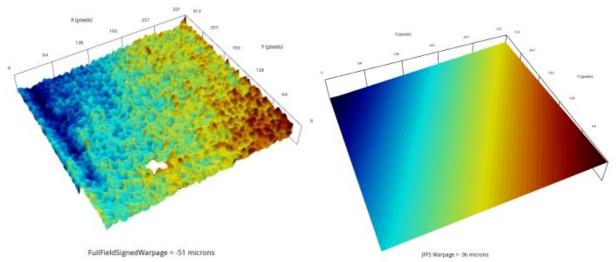

Figure 12.(a) Die warpage + Tilt (b) Die Tilt Only

Different die surfaces that were measured for this technique, including numbers from many of the figures previously shown, are summarized in Table 1 below. Die angle is shown either including and excluding the warpage of the die. For the samples used in this study, die tilt levels were generally rather low.

Table I. Summary of Found Die Tilt Using Shadow Moiré

Die #	Die Angle Including Warpage	Die Angle Removing Warpage
1	0.269°	0.245°
2	0.246°	0.240°
3	0.083°	0.112°
4	0.102°	0.102°
5	0.055°	0.049°
6	0.072°	0.067°

Furthermore, speed and ease of use should not be overlooked in comparing shadow moiré to other die tilt measurements solutions. Shadow moiré takes only two seconds to capture over 1 million data points. Whereas as point to point based technologies are dependent on quantities of measurement points. Additionally, shadow moiré solutions can process multiple areas in a single measurement. This makes loading a full JEDEC tray and capturing die tilt of all samples within that tray possible. Different technologies for deciding pass/fail, as well as locating samples in space, exist within available shadow moiré software. Figure 13 shows an example of samples in a JEDEC tray, where all samples have been located in space with an edge recognition approach. Testing die tilt in high volume becomes very practical using shadow moiré in a recipe style approach.

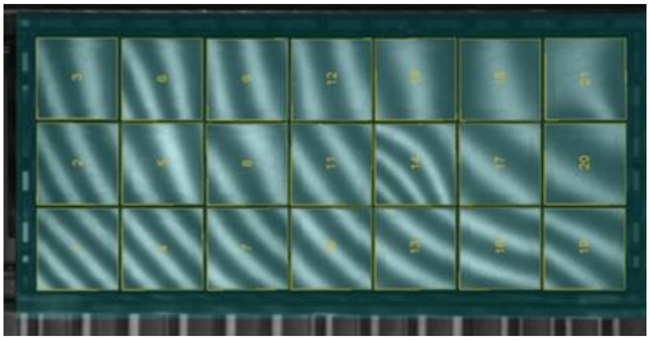

Figure 13. JEDEC tray with automated Part Tracking

VIII. Extended Applications

The concept of capturing shadow moiré data with relative tilt between two independent surfaces can be extended beyond the concept of purely die tilt, as focused on for this paper. M. Anselm in "A.R.E.A – Component Warpage: Issues with Measurement and Standardization" discusses not only warpage, but parallelism in surface mount attachment [7]. Figure 14 is borrowed from this paper. In this graphical example the molded side of the component can be measured for warpage and warpage + relative tilt to the PCB can be plotted in the same manner as a die to a substrate.

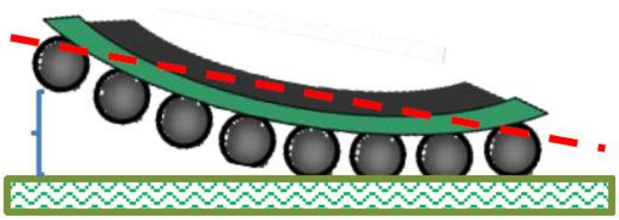

Figure 14. Nonparallel component (from [7])

This is one such example. The concept can be extended to various other applications, such as die-die attachment, multiple die surfaces, 3D packaging, pedestals for optics, etc.

IX. Conclusion and Future Steps

The paper presents how and why shadow moiré is, not only a metrology for measuring surface warpage, but also a metrology that can extract useful information from discontinuous surfaces. The shadow moiré technique has the disadvantage of not being able to test completely specular surfaces, though recent technological improvements have extended the range of measureable surfaces. The advantages of shadow moiré for measuring die tilt include throughput, automation, reproducibility for different operators, and the removal of die warpage from tilt calculations. Given these advantages, shadow moiré could be used for die tilt measurement for high volume manufacturing quality assurance. While focused on die tilt for this paper, the implications of working with discontinuous surfaces and shadow moiré data extend beyond die tilt to other discontinuous surface applications.

The samples studied for this paper had generally low levels of tilt and likely in all cases would not have presented problems. Using shadow moiré on a larger subset of samples covering many different types would further substantiate this process. Some further software automation can be done to improve the speed and ease of use of shadow moiré for specifically calculating die tilt.

Acknowledgment

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