Measuring Die Tilt Using Shadow Moiré Optical Measurements; New Techniques for Discontinuous and Semi-Reflective Surfaces – Phase 2

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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 focuses on case study data for samples with two or more separated planes. Die tilt measurement techniques from phase 1 of this study are applied to the case study data. 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.

I. Introduction

This paper is a phase 2 study building on the finding of an earlier study. Phase 1 of the related study on die tilt measurements, using phase stepping and the shadow moiré technique, covers approaches and techniques to use shadow moiré for the measurement of the tilt of a die surface, or of other elevated surfaces separated as two independent planes. [1] Shadow moiré is an optical full field warpage/flatness measurement technique that uses directional light, a camera, a vertical motion system, and a piece of glass with periodic opaque lines in the glass. [2] Traditionally, shadow moiré measurements have been used to define warpage or flatness of a continuous surface having no ability to measure surfaces where height changes occur suddenly, by either exceeding a maximum slope of 0.2 or a maximum step height between two adjacent points no greater than approximately 100 microns, depending on grating pitch.

The initial phase 1 study went on to detail the approach of die tilt calculation based on shadow moiré images, having a common reference plane, the grating, between the two separated surfaces. Additionally, new approaches to data acquisition using 12 bit phase data and floating point phase calculations were proposed to further enable measurement of semi-reflective die surfaces or dark substrate areas. Even with these improvements a key point for the shadow moiré approach for die tilt measurement, is that it does not work for all surfaces. In the phase 1 study, 3 of 4 observed samples types were measureable and 1 of 4 was not, based on the specularity of the measured die surface. Samples that are too specular appear like a mirror without any shading. Many surfaces with high levels of specularity can still be measured if some of the light reflects in a diffuse manner. In all cases, the sample type should be validated as viable for the shadow moiré technique, before pursuing this approach for die tilt measurement. In laboratory use, surfaces measured by shadow moiré are often coated with a white paint or talc powder before measurement, but die tilt measurement is meant to be an outgoing QC procedure, and not conducive to sample preparation.

Phase 2 of this study goes on to propose a method for measuring the standoff height of an elevated platform, or exposed die, based upon an initial height estimation made by the user. Specific accuracy requirements are discussed for the initial height prediction. Some strategies have been proposed, historically, for using the shadow moiré method to measure step heights. [3] However, this type of approach requires extra measurement time and more involved moving parts. Whereas, much of the goal for a shadow moiré based die tilt solution is to maximize die QC throughput, maintain high system robustness, and keep cost of goods down.

Additionally, a case study is performed on an exposed die flip chip. Other techniques for measuring the tilt of a die relative to a surrounding substrate are available in the industry. Reference [4] covers one such method, using an optical non contact scanning probe system. The specifics of the sample used in the case study are not provided for propriety reasons. The flip chip sample is between 25-30mm in size and close to square.

II. Uses of Die Tilt and Shadow Moiré on Discontinuous Surfaces

Similar to Phase 1 this paper does not focus on reasons to measure the tilt or angle of a die or offset surfaces. The focus of the paper is one of new methodology along with a case study covering the effectiveness, strengths, and weaknesses of using shadow moiré for die tilt measurement. 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. [5] – [7].

The limitations for using shadow moiré to measure discontinuous surfaces are discussed in Reference [1], as well as in older publications. A shortened explanation of this step height limitation is given as follows.

Early shadow moiré, prior to any phase stepping technology, was based on counting transitions of dark and light fringes (Fig **1**). The geometry of shadow moiré allows calculation of a specific height associated with each fringe, known as "Fringe Value". 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°.

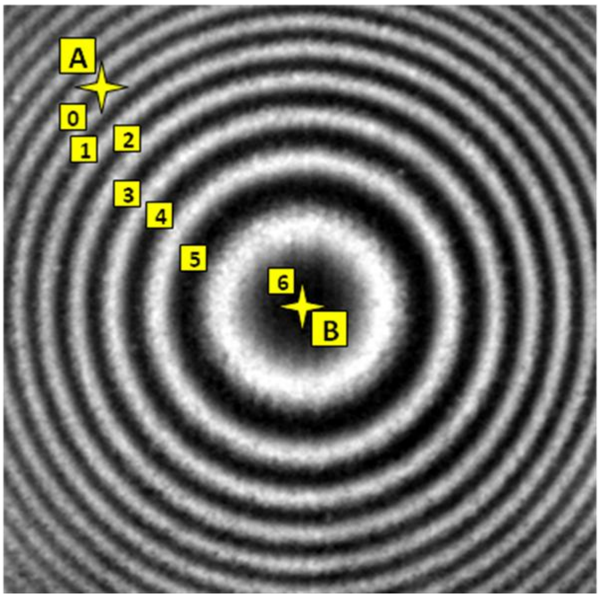

Fig 1. Shadow moiré intensity image

III. Shadow Moiré Workflow to Measure Die Tilt Angle

While Phase 1 of the die tilt study was mostly done by hand and implementation was more theoretically, software development has since been underway, and die tilt angle now exists as a gauge in Akrometrix's Surface Analysis processing software. This development is mentioned briefly here only to support the workflow and scalability of the case study to calculate die tilt angle in a batch fashion and with minimal user interaction.

Workflow to measure die tilt angle includes:

1) Confirm if the optics of the die surface allows shadow moiré measurement, done by taking a physical shadow moiré measurement and confirming phase amplitude threshold max/min.
2) Identify multiple sample locations in the shadow moiré field of view. This step only needs to be done once per sample type and layout. An example is given of a JEDEC tray of samples in Fig **2**.
3) Identify the Die and Reference surfaces in the software GUI. An example is shown in Fig **3**. These locations are reused for each surface, so again this step is done only once per sample type.
4) Repeat the process of identifying reference surfaces and die surfaces if multiple die locations exist per sample. Die tilt angle can be shown from die to die or substrate to multiple dice.
5) Measure multiple groups or lots of samples as desired. Measurement time is 2 seconds per group/lot, regardless of sample quantity, plus unload and load time.
6) Use files created in steps 2) to 4) to batch process all results together.

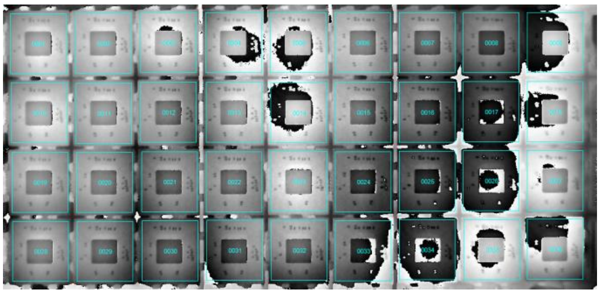
Fig 2. Identifying sample locations (phase image)

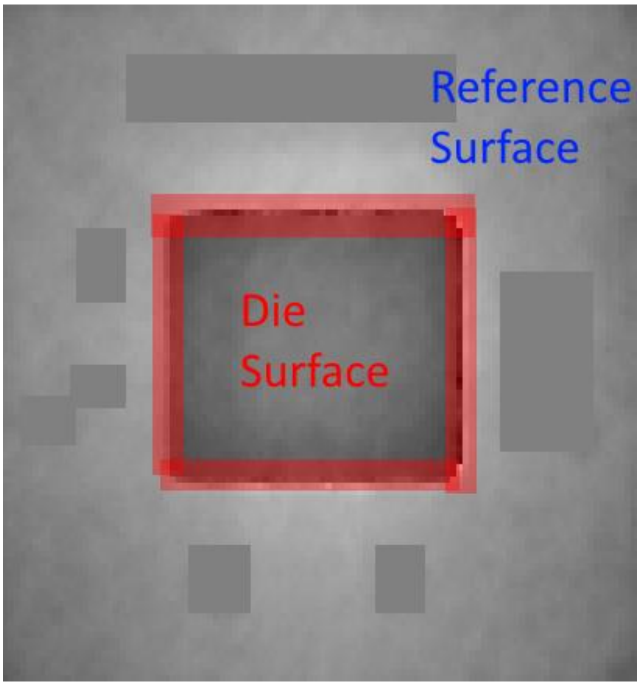

Fig 3. Software interface example, for two planes

Die tilt angle can be calculated from the data sets within the batch processing interface.

IV. Flip Chip Case Study Test Plan

60 samples are measured in two single shadow moiré measurements. The samples are measured inside of JEDEC trays, as received. As discussed earlier, extensive details on the flip chip sample are not provided for propriety reasons. The chips come in a 4x11 layout JEDEC tray. The samples themselves are already production quality devices that likely received outgoing quality checks, thus consistent and well behaved data is expected. The focus of the case study is more to validate the concept and throughput of the solution. Gauge results from the 60 samples are collected considering the following variables:

1) Height of the die from the substrate using a newly proposed technique to predict this height given an initial estimate
2) Die tilt angle with and without compensation for die warpage
3) Throughput time per batch/JEDEC tray

V. Using Shadow Moiré to Measure Discontinuous Step Heights, Given an Initial Height Estimate

As discussed in section II, shadow moiré is traditionally not used to measure surfaces with sudden changes in height. To understand this limitation and ways to circumvent this limitation a closer look at the shadow moiré phase stepping algorithm is required. The first step for shadow moiré measurements is to determine the height associated with a single fringe period, called Fringe Value. Considering again Fig 1, a counter moves across 6 total fringe periods. The theoretical calculation for Fringe Value is:

$$W = \frac{P}{\tan\alpha + \tan\beta} \qquad (1)$$

where W = Fringe Value
P = pitch of the grating lines
α = angle of illumination
β = angle of observation

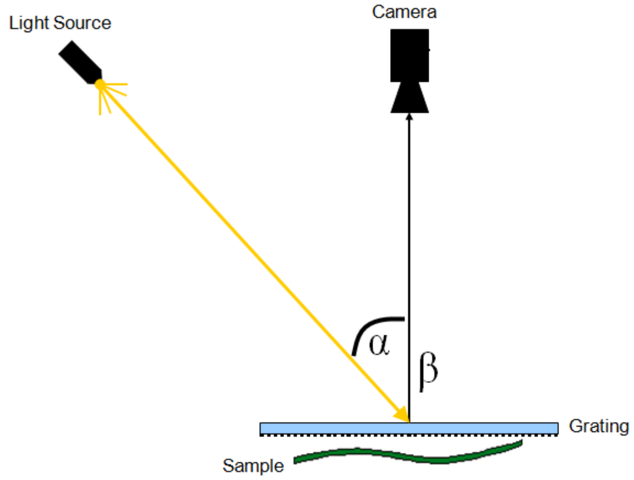

Fig 4. Basic shadow moiré setup

In practice, the Fringe Value is calibrated by comparison with a known step height calibration block, to establish a more accurate Fringe Value.

With a known height per fringe the "phase" of each single pixel can be determined by extracting the grayscale intensity value from each image, called intensity images, taken during the phase stepping process. A four step phase stepping is used in this case. The sample and grating are moved apart the distance of the Fringe Value / 4 between each image, representing a 90° shift in the periodic fringe pattern. The phase calculation can be simplified to:

$$\Phi(x, y) = \arctan\left(\frac{I_4 - I_2}{I_1 - I_3}\right) \qquad (2)$$

where I values are grayscale intensity values.

To this point, none of these calculations are limited by step heights. Thus, even across sudden steps heights, the phase term, Φ, is still valid. It is this concept that is critical to the forthcoming approach to discontinuous step heights, given an initial height estimate.

The final equation converting phase data to Z height information is where step heights pose a problem. The equation for height is as follows:

$$Z(x, y) = W\left(N + \frac{\Phi(x,y)}{2\pi}\right) \qquad (3)$$

where N represents "Fringe Order", an integer.

Because phase occurs in a periodic manner, in order to translate phase data to Z height a counter integer must be tracked whenever a new phase begins. Fig 5 and Fig 6 visualize this concept.

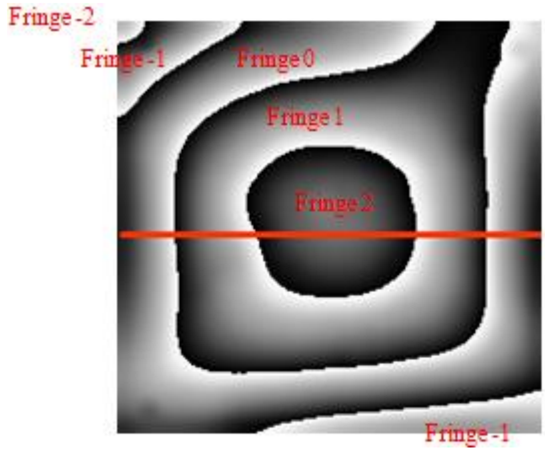

Fig 5. Phase image with Fringe Orders

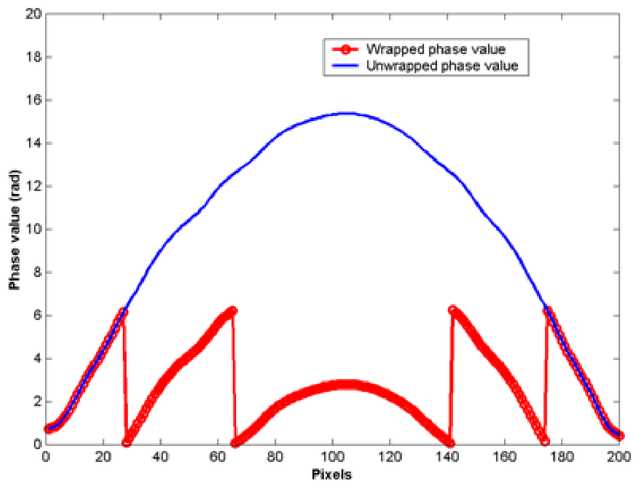

Fig 6. Phase values from red line in Fig 5 with and without Fringe Order included

In order to determine a correct Fringe Order, N, a steady change in height is required. The height between the center and corner of Fig 5 cannot be determined without the information in between the two areas, showing the quantity of fringe transitions. Thus the only problem is to determine a correct value for N, which must be an integer.

Given this information a new strategy is proposed to use an approximate height value input from the user and then use the available phase portion of the shadow moiré equation to determine a more accurate Z height. The same sample used in the upcoming case study of die tilt is used to validate this approach. To look more closely at the numbers involved with the prediction of height and measurement accuracy, the initial height prediction must be within the Fringe Value / 2, and the accuracy for the shadow moiré measurement is Fringe Value / 100. For this case a 100 line per inch (LPI) grating is used so actual values translate to a required prediction accuracy of 127 microns and a final Z height accuracy of 2.5 microns.

Using Digital Fringe Projection (DFP) the step height of the sample studied is first determined to be used as our prediction. The DFP technique is capable of measuring surface step heights, but has worse accuracy, smaller field of view (allowing lower throughput), and is more sensitive to less optimal (unpainted) surfaces. Here the technique is accurate to 5 microns and easily effective in determining an initial height estimate. A 3D surface rendering of one such sample measure with DFP is shown in Fig 7. In Fig 8, an average step height between substrate and die areas is calculated.

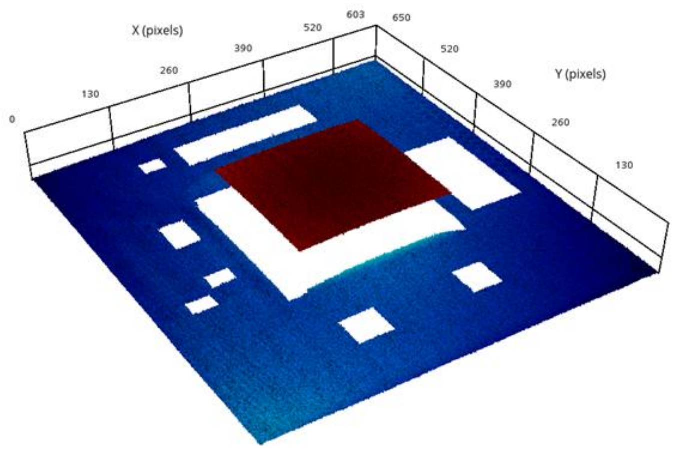

Fig 7. Flip chip with exposed die measured with DFP

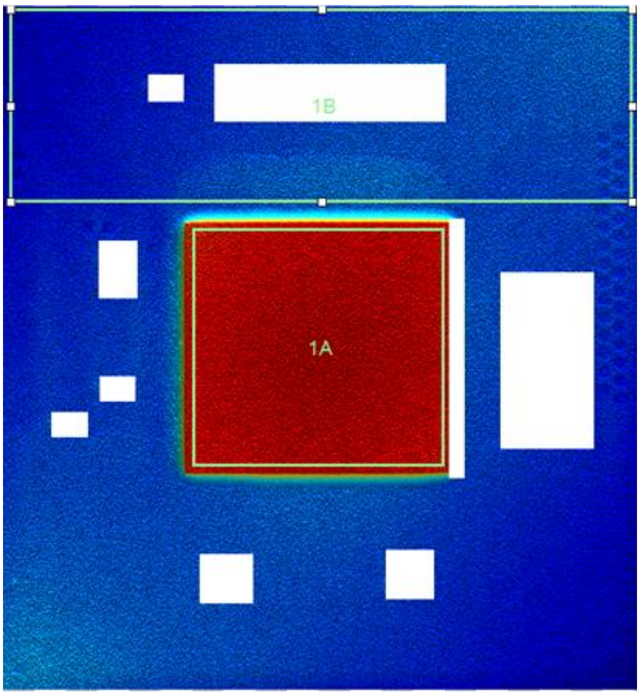

Fig 8. Determine flip chip step height

From this study the estimated step height for the die was 470 microns. Without the step height prediction the shadow moiré unwrapping across the sudden height change is likely to produce an incorrect result. However, the error in this result is always a discrete error being the Fringe Value multiplied by an integer. As an example, the flip chip sample is analyzed as measured by standard shadow moiré algorithms, shown in Fig 9. In this case the die surface is interpreted as 2 full fringe values, 508 microns (2*254 microns/fringe) lower than the actual correct data set and is incorrect.

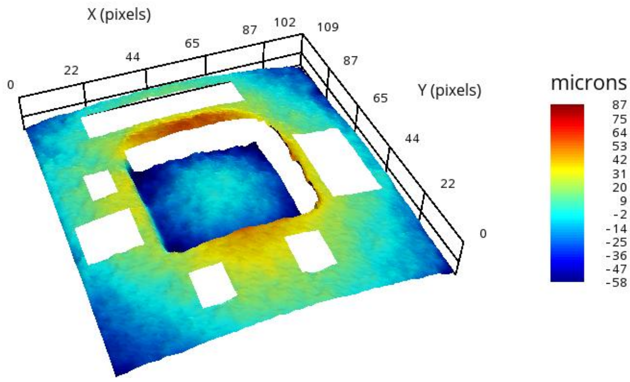

Fig 9. Incorrect shadow moiré processing of phase image

Visualized in a different way Fig 10 shows the actual die height, the shadow moiré interpreted die height and other possible values created by changing fringe orders, N.

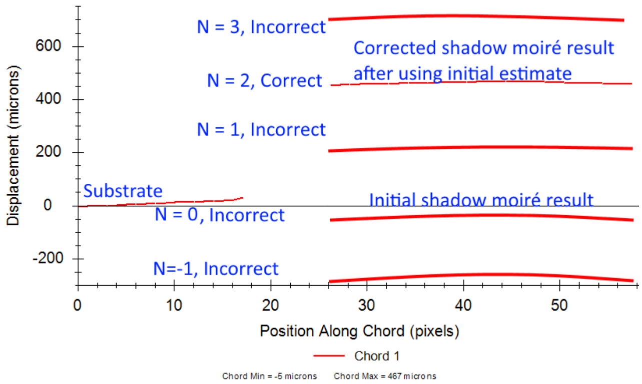

Fig 10. Coordinate plot of possible step heights

VII. Flip Chip Die Height Case Study Results

The results from the case study concerning predictive die height are shown in Table 1. Note that die tilt angle calculations are in no way dependent on a prediction or measurement of the absolute die height, thus the value of this section stands alone from value added by die tilt angle calculations.

Table 1. Predictive step height results

Samples measured	60 samples
Die height prediction	470 microns
Minimum Die height found	439.1 microns
Maximum Die height found	481.8 microns
Average Die height found	460.3 microns
St. Dev. Die height found	12.0 microns

Variation in die height is hypothesized to be more a result of overall package warpage difference between samples. The consistency and range of the results suggests that both the die height prediction and die height measurements are within expected tolerance, as die height never varied outside of 31 microns from the predict nominal, thus well inside the Fringe Value / 2 (127 micron) requirement. In practice a tighter threshold than Fringe Value / 2 can be used to avoid inaccurate calculation of fringe order. In this case using Fringe Value / 4 as a tolerance threshold for an acceptable gauge result answer is a suggested improvement to aid the reliability of this approach. Tightening this allowable range would generate a failed calculation instead of false information if the estimate and measured results were between 64 to 127 microns different, in the case of the 100 LPI grating.

VIII. Flip Chip Die Tilt Angle Case Study Results

For the purpose of comparing shadow moiré with point to point based technologies used to measure die angle the die tilt angle is processed in one of two ways. The first is to process the die corners as measured, as would be done in a point to point based system. However, one could argue that with full field data a more realistic value for die tilt angle can be generated between the die and substrate by fitting both data sets to a plane instead of single points. To further this point the die surface is shown in Fig 11 including both tilt and warpage of the die surface.

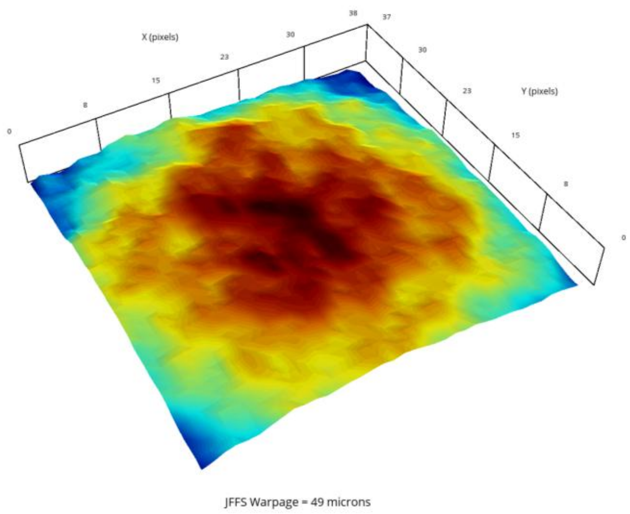

Fig 11. Die surface showing both tilt and warpage

For the purpose of comparison die tilt angle is calculated based on both the warped die and a plane fit die. The same data set from Fig 11 is shown in Fig 12 after a 1st order plane fit has been applied, leaving only relative tilt between the die and substrate.

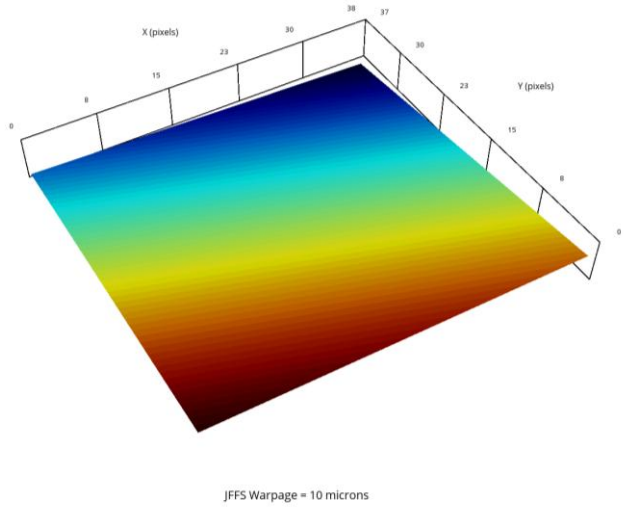

Fig 12. Die surface with tilt only

The concept of comparison between the two methods is covered in more detail in phase 1 of the study. [1]

Results for the case study showing die tilt angle are shown in Table 2.

Table 2. Die tilt angle (DTA) results

	DTA including die warpage	DTA die fit to plane
Samples measured	60 samples	60 samples
Minimum DTA	0.006	0.003
Maximum DTA	0.096	0.075
Average DTA	0.040	0.040
St. Dev. DTA	0.019	0.018

As expected, die tilt angles are very low for this case study. For the given data set, minimal difference is seen between the two different approaches to angle calculation.

IX. Shadow Moiré Room Temperature Throughput

Timing for measurement of die height and die tilt angle were also evaluated during this case study. A primary reason to use shadow moiré to measure these gauges is purely for throughput. Because shadow moiré is a full field technology, once the test plan is established for a single sample type and layout, which is also a quick process, running high volumes of samples scales very well. This throughput is complimented by software to qualify pass/fail limitations for good or bad samples based on gauge information. Therefore, for high volume, processing time is essentially negligible and the bottleneck becomes equipment time.

Measurement time for a batch or tray of samples with current solutions is mainly taken up by load and unload time, as the actual measurement is only 2 seconds. Additionally, a fixture or jig should be used to ensure repeatable placement of the sample for each load step. With a manual loading solution the samples used in this case study had an approximate total cycle time of 20 seconds, taking care with the samples and moving somewhat carefully. The case study in question had 44 samples per tray, thus a throughput of 7920 samples/hour.

Throughput time could be further improved by automated handling. The throughput of 7920 samples/hour does not include any sorting of good and bad samples, which could also be done downstream.

X. Conclusions

Shadow moiré technology has extended usability and measurement application value outside of its most common use cases. The measurement methodologies shown here were developed purely through software and process improvements, thus extending useful applications without adding costly hardware. Highly specular surfaces, such as die surfaces, remain challenging for optical metrologies relying on diffuse light reflectance, such as shadow moiré and digital fringe projection; though software development has narrowed the gap of sample surfaces that cannot be measured with shadow moiré.

Shadow moiré can be used to measure sudden step heights, given an accurate initial estimate within 127 microns (in the case used in this study) of the actual height. Using shadow moiré to predict step heights should be used with caution, as an incorrect input estimate greater than the allowable tolerance will lead to incorrect output data. When used correctly the resolution of the measured step height is increase by 50X from the initial estimate. A case study of 60 samples is used to validate the approach

Die tilt angle has a fully established workflow in software, offering some advantages over some comparablee techniques in terms of throughput. Absolute measurement accuracy may likely be lower than point based measurement techniques in some cases, but angle calculation can be taken on a plane fit of the die surface instead of raw data of the die height, which factors in warpage. The case study of 60 samples resulted in very low die tilt angle numbers.

Throughput for quality assurance to measure both die height and die tilt using shadow moiré technology is high, at 7920 samples/hour. Throughput is unchanged whether measuring one or both gauges in this example. Sample handling automation could further improve measurement throughput.

It is worth noting that the concepts shown for height and angle between die and package can also be applied on numerous surfaces offset from one another, such as a package on a PCB.

Acknowledgments

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